EVALUATION OF SULFUR MODIFIED EMULSIFIED ASPHALT FOR ROAD CONSTRUCTION

BY

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Dedication

Every challenging work need self-effort as well as guidance of elders especial who were very close to our heart. My humble effort I dedicate to

My sweet and loving Father, Mother and my wonderful wife

Whose affection, love, encouragement, prayers of day and night make me able to get such success and honor

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In the name of Allah, the Beneficent, the Most Merciful. All praises and thanks are due to Allah, the Lord of the world for the successful completion of this research work. May His peace be upon the last messenger, Prophet Muhammad, his family and companions.

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Finally, I pray to Almighty Allah to reward all those who contributed, either directly or indirectly, towards the success of this work.

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LIST OF ABBREVIATION

ANOVA	:	Analysis of Variance
AASHTO	:	American Association of State Highway and Transportation Officials
ASTM	:	American Society for Testing and Materials
CBR	:	California Bearing Ratio
EA	:	Emulsified Asphalt
ORAC	:	Optimum Residual Asphalt Content
ESA	:	Emulsified Sulfur Asphalt
ITS	:	Indirect Tensile Strength
FHWA	:	Federal Highway Administration
AEMA	:	Asphalt institute and the Emulsion asphalt Manufacture’s Association
M_R	:	Resilient Modulus
μ	:	GNU
α	:	ALPHA
EAL	:	Equivalent ۸۰ kN Axle Load
SEA	:	Sulfur Extended Asphalt
SAS	:	Sulfur Asphalt Sand
BAEM	:	Basic Asphalt Emulsion Manual
USCS	:	Unified Soil Classification System
SEA	:	Sulfur Extended Asphalt

THESIS ABSTRACT

Name: YASSER MOHAMMED GHALB ALGHRAFY

Title: EVALUATION OF SULFUR MODIFIED EMULSIFIED ASPHALT FOR ROAD CONSTRUCTION

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The primary aim of this study is to assess the engineering properties of Emulsified Asphalt (EA) and 30% sulfur modified emulsified asphalt (ESA) treated mixtures for their potential applications in roads. Also, to generate rutting models which have been obtained to predict the permanent strain in the base using VESYS software.

The test procedures conducted on three types of soils: Marl, dune sand, and sabkha that cover important geographical areas of the Kingdom of Saudi Arabia. The design mixtures were subjected to Marshall Stability test, Indirect Tensile Strength (ITS) test, Resilient Modulus (M_R) test, and Static triaxial test whereas, the behaviors of mixes under dynamic loads were studied using dynamic triaxial test to generate useful laboratory data that can depict the performance of such mixes under traffic conditions and simulate the rutting performance of base courses using VESYS model.

The results showed that resilient modulus has improved for sabkha soil with (Emulsified Sulfur Asphalt) ESA, but this impact was negative with marl and dune sand. Moreover, ESA blend shows lower water absorption compared to their EA blend; durability increased when ESA was used as compared to EA. The use of the ESA slightly reduced the value of permanent deformation for mixtures with sabkha while it had a negative impact on the

ability to resist collapse time; permanent deformation has increased when the ESA was used with marl and dune sand compared of EA.

The results from both the dynamic Triaxial test and VESYS model results have been used in developing design charts and guidelines for the selection of a base thickness for the allowable traffic.

ملخص الرسالة

الأسم: ياسر محمد غالب الغرافي

العنوان : تقييم خليط المستحلب الاسفلتي مع الكبريت لبناء الطرق

قسم : الهندسة المدنية

التاريخ : ديسمبر ٢٠١٣

يهدف هذا البحث الى تقييم الخواص الهندسية لمستحلب الأسفلت العادي والمستحلب الاسفلتي المحسن بنسبه ٣٠٪ من الكبريت و كذلك دراسه إمكانية استخدامهما مع التربة المتوفرة محليا مثل الرمل الجيري ورمل الكثبان و السبخات في الطرق كطبقه رصف نظراً لندرة مواد الرصف ذات النوعية الجيدة في بعض مناطق المملكة العربية السعودية .

اختيرت طريقة تصميم الخلطات الباردة (طريقه مارشال المعدلة) لتحديد المحتوى الامثل للمستحلب الاسفلتي و المستحلب الاسفلتي المحسن بالكبريت و كانت نسب المستحلب الاسفلتي العادي و المحسن المستخدمه بين ٣٪ إلى ١٨ ٪ من الوزن الجاف للتربة واضيف الاسمنت البورتلاندي بنسبه ٢٪ الي الخليط لاعطاءه مقاومه اوليه .

لتقييم الخواص الميكانيكيه و محاكاة التشوه الناتج من تاثير مرور العربات (التخدد) استخدمت العديد من الاختبارات المعمليه و شملت هذه الاختبارات اختبار الشد غير المباشر و اختبار القص و اختبار معامل المرونه و اخيراً اختبارات التشوه .

حللت النتائج إحصائيا وتم عمل نموذج للتشوه (التخدد) باستخدام برنامج (VESYS5W) واعتماداً علي النتائج استنبطت رسوم بيانيه لتصميم طبقه الاساس المعالج بالمستحلب الاسفلتي او المعالج بالمستحلب الاسفلتي مع الكبريت .

أظهرت النتائج تحسن معامل المرونه للسبخه مع مستحلب الاسفلت والكبريت بينما كان التاثير سلبياً مع الرمل الجيري و الكثبان الرمليه. كذلك كان التاثير سلبيا بالنسبه لقوه القص لانواع التربة الثلاث. و علي العكس من ذلك ابدت التربة المحسنه بالمستحلب مع الكبريت مقاومه أفضل في امتصاص الماء عن تلك التي تم تحسينها باستخدام المستحلب الاسفلتي فقط مما انعكس ايجابياً على المتانة. ان استخدام المستحلب مع الكبريت قلّل بشكل طفيف من قيمة التشوه بالنسبة للسبخة مع ملاحظة انهيار العينات خلال وقت اسرع بينما كان تاثيره سلبياً بشكل عام على التشوه في الرمل الجيري والكثبان الرمليه . و من الجدير بالذكر ان مستحلب الاسفلت والكبريت كان له تأثيراً ايجابياً في زيادة مقاومة التشوه عند ازدياد الحرارة.

CHAPTER 1

INTRODUCTION

The most widespread form of stabilization is compaction, which improves the mechanical stability for any soil. Nonetheless, compaction alone is often not enough. So in this case stabilization by adding additives will be used, this stabilization is defined as blending and mixing materials with a soil to improve the soil's strength and durability. EA is a famous type of additives which used in soil stabilization. It is used for many applications such as airfields, traffic pavements, parking and, storage areas where an all-weather surface is required. Also, Surface treatments are used to provide dust control.

EA stabilization of pavement material is usually intended either to introduce some cohesion into non-plastic materials or to make a cohesive material less sensitive to loss of stability with increased moist. The process is more successful with granular material than with cohesive material. It is, therefore mainly used on base and, to a lesser extent sub-base materials. Using a mixture of bituminous and cementation's binders together has the advantage of improving strength as well as increasing cohesion and reducing moisture susceptibility. EA stabilization of pavement material improves the performance, even with poor quality pavement materials [1].

1.1 Problem Statement

Kingdom of Saudi Arabia like any country, needs to minor roads which are necessary to connect settlements and agricultural farms with main highways. Locally available soils should be utilized in the most effective manner for construction of these roads. Due to the high cost of scarce good quality aggregate and also shortage in the good quality of construction materials of roads along the coastal regions of the Saudi Arabia, the upgrading of marginal abundant material such as marl, dune sand, and sabkha are very important.

Most important parts of Saudi Arabia are covered with the dune sand, which is characterized as poorly graded soil with high permeability. In addition to that, marl and sabkha are available in some parts in Saudi Arabia, which have a poor strength with change their properties with water. But in some cases, it is usually required to use these materials as sub-grade layers or as a backfill in base and sub-base layers of roads and highways so some kinds of stabilization are required to improve the characteristics of these materials.

On the other hand, EA represents an attractive option for local use. The large network of roads compared to the low population makes the maintenance cost of such a system very expensive, if only hot asphalt overlay is considered (as is the case now) [2].

The construction cost of roads may be to increase expected to increase drastically so use of EA allows for the use of locally available dune sand, marl, and sabkha which are less costly for road.

EA provides an easy means of stabilizing dunes for protection of roads and industrial areas. Moreover, EA can be used for preparation of industrial sites. Therefore, EA appears to be attractive for use in Saudi Arabia and deserving of further study [2].

1.2 Objectives

The main objectives of this study are:

1. To use EAS utilizing 30/70 sulfur asphalt for the stabilization of local indigenous Eastern Saudi soils, including dune sand, marl, and sabkha.

2. To compare to those prepared with regular EA.
3. To simulate the permanent deformation using dynamic triaxial test and VESYS rutting model.

1.3 Study Approach

This research consists mainly of a laboratory study of mix properties as a function of different factors (i.e., ESA content, EA content, and soil types). Slow setting ESA will be used to stabilize marl, dune sand and, sabkha and develop a mix that can be used for road bases construction under light to medium traffic. A 2% Portland cement will be added to the stabilized soils to accelerate curing process and to reduce stability loss due to water damage. Also, simulate permanent deformation using dynamic triaxial test and develop a model to predict rutting and structural behavior using simulation procedures.

This thesis covers a theoretical review, methodology, results and analysis from laboratory investigations. The thesis is composed of six chapters as shown in Figure 1.1. A brief description of the contents of each chapter follows:

Chapter one is an introduction that outlines the background of the investigation, problems, objectives, and research program. Chapter two presents a review of bitumen emulsified asphalt, sulfur asphalt, and rutting models. The common tests for mix design are presented in Chapter three. Chapter four reviews the test results and Chapter five presents a rittung analysis. Finally, Chapter six presents the conclusions and recommendations.

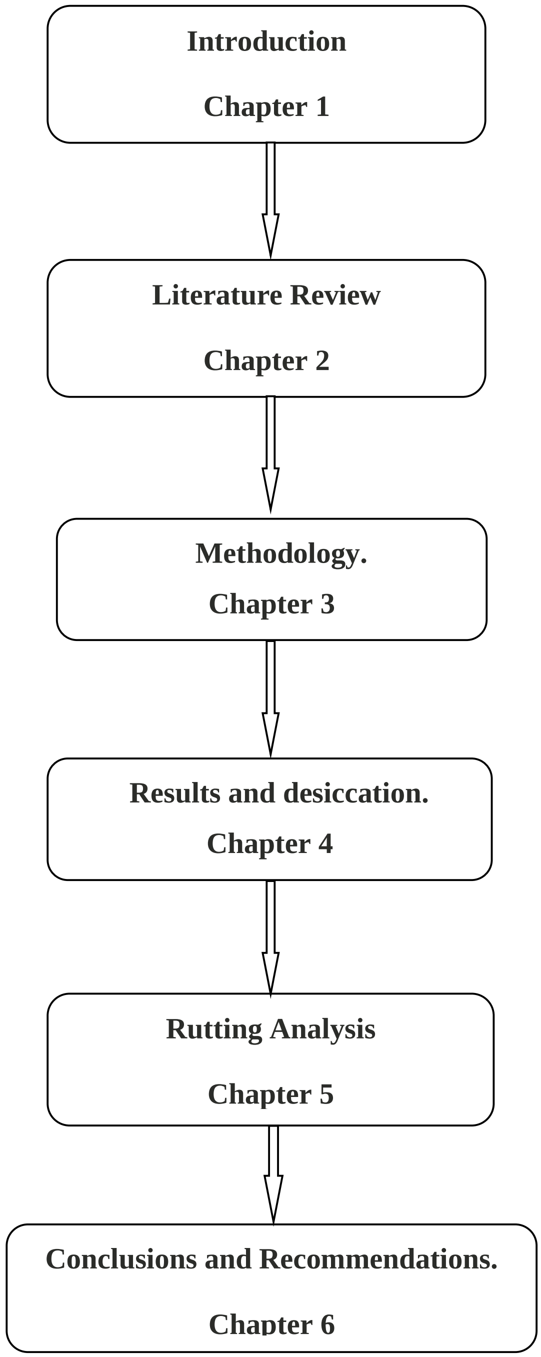


Figure 1.1: Study approach

CHAPTER 2

LITERATURE REVIEW

2.1 Asphalt Emulsions.

Asphalt emulsion is a combination of asphalt binder and water that includes an emulsifying agent which affects in asphalt to become it mixed with the water. Asphalt emulsion may be either anionic with electro-negatively charged asphalt globules or cationic with electro-positively charged asphalt globules, depending upon the emulsifying agent [3].

The first used of asphalt emulsions was in the early part of the 20th century where present 5% to 10% of paving-grade asphalt was used in emulsified form. The asphalt emulsion has many advantages compared to hot asphalt and cut back binders which related to the following [4]:

1- Lower application temperature,
2- Compatibility with other water-based binders like rubber latex and,
3- Cement and low-solvent content.

In the manufacture of asphalt emulsion, a mixture of emulsifier solution ('soap') and hot asphalt are passed through a colloid mill, where the emulsification takes place. The soap solution contains water, emulsifier, acid or base and, if required, a stabilizer such as calcium chloride.

Well-graded dune sands with sufficient silt-clay material responds well to emulsions, also Portland cement in trace quantities was required to improve the water susceptibility of the mixtures. Because of its superior bonding to siliceous aggregate and its rapid setting tendencies, cationic emulsion is preferred in dune sand stabilization. Recommendations concerning mixing and compaction moisture are presented [5].

Study on soil stabilizers on dune sands and silty dune sands from the Bethel, Hooper Bay and, Michael areas of the Yukon-Kuskokwim river delta region of Alaska concluded that, when EA mixed with Type III Portland cement, it could stabilize the soils enough to use for wearing course or sub-grade material for highway and airport construction [6] .

Use of bituminous emulsion to stabilize lime-treated clays were studied [7], effect of lime content, molding moisture content, modification curing time, emulsion type and curing temperature on the unconfined compressive strength of the stabilized material was investigated. The unconfined compressive strength increases with the increase of lime content, molding moisture content and, curing temperature. However, the effect of modification curing time is dependent on the soil type and percentage of emulsion used. The effect of emulsion type depends on whether rapid-set or slow-set emulsion is used and on the type of treated soil.

Effect of adding cement and asphalt emulsions on composition and properties of two soil samples from the Bethel, and Alaska area was examined to find out if these soils can be improved by adding cement and asphalt emulsions for use as sub-base and base course materials for airfield and roadway applications. Three cationic slow-set (CSS-1) emulsions from different manufacturers were compared. Test results confirmed that, the use of an emulsion specially selected for the particular soil properties can result in major performance improvements over standard production emulsions of the same grade. For the soils tested, similar strength levels were reached with 30 to 40% less of the specially select emulsions. In addition to that, Test results demonstrated that, cement contents below 1.5% was generally of no benefit and cement contents of 2% consistently increased the mixture cohesive strengths from 20 to 80%. Tests of dune sands having different fines contents indicated that the optimum fines content for emulsion stabilization falls between 12 and 20% [8].

When using emulsion asphalt with dune sand [2], the mix properties were changed Specials by the inclusion of crusher fines in the mix. Also, to that, the stability, resilient modulus, fatigue, and rutting characteristics of such mixes were improved significantly. Thickness design charts were developed for the designed mixes, which proved to be suitable for use in hot, arid areas. In conclusion, Pavement thickness was significantly reduced when crusher fines, cement, and dune sand blends were treated with EA.

Using of slow setting EA and medium curing cutback asphalt to stabilize marl and sand obtained from the Eastern Province of Saudi Arabia was studied [9], the addition of 2% and 4% lime and Portland cement was applied to the stabilized soils to accelerate curing process and to reduce stability loss due to water damage. The results of this research indicated that the stabilizing agent has both enhanced strength and resistance of the analysed soils to water damage. Cement additive was found to be more effective than lime. Cement and bitumen blends are most suitable for soils with a PI less than 6 and having less than 25% passing the No. 200 sieve [1].

The polymer emulsions do offer significant strength gain and added strength under wet conditions [10].

Some polymer emulsions achieve compressive and retained wet strengths on the same order as the cement stabilized soils at lower additive levels. Toughness values reveal that some soil polymers exhibit significantly higher values for both the wet and dry testing condition than soil cements, indicating significantly higher strains were attained at maximum applied stress. No significant differences in the retained wet strength and toughness were found between the polymers and cement soil additives. Stabilization of silty sand with emulsions may result in compressive strengths and strain to failure superior to those observed with cement. However, given that the emulsions 'cure' by water loss, it takes significant time for the beneficial soil improvements to be realized [11].

The addition of Portland cement on EA mixtures was studied [12], by changing the percentage of this additive from 0% to 6% as mineral filler. Moisture-damage performance was evaluated using the ratio of measuring the resilient modulus of mixtures, before and after soaking in water. Mixtures without the addition of cement failed after six hours of conditioning. However, EA mixtures with cement showed better water resistance and an increase in the resilient modulus.

The amount of polymer deposited on the surface of the soil particle depends on the concentration of the polymer added and the degree of mixing with the soil [13].

The possibility of the stabilization of expansive clayey soil pre-treated with lime, and EA addition was investigated [14]. The soil was classified as medium to high expansiveness in naturally. The pre-treatment of soil was accomplished with (0.5, 1.0, and 1.5%) lime addition by weight. After a short period, EA was added with different dosages namely (2, 4, 6 and 8) by weight, for optimum percentages of EA to give the most useful stabilization aspects. The result of adding lime alone indicated that there was a significant reduction in soil plasticity, 1.5% of lime addition changed the clayey soil towards non-plastic types. The EA addition to the mixture, resulted in a slight increase in the plasticity, but their values in the whole, remained below the value of the natural soil. Results also showed that, the decrease in the specific gravity with the EA addition as well as, a general reduction, compatible with the increase in the optimum moisture contents. The absorption values of the treated soil with the EA showed consequent reduction as compared with the original one. A significant reduction in swelling pressure and swelling percent were noticed as well as an improvement in some values of the unconfined compressive strength at low percentages of EA addition, compatible with reduction in values of the high percent additions.

The effect of cement on the fatigue properties of cold recycled mixes with bitumen emulsion (CRME) was reported [15], to build up fatigue models for these mixes, extensive indirect tensile fatigue and resilient modulus tests were conducted at different temperatures (varying from -10 to 25°C) and curing times (varying from 7 to 120 days). The results of this study indicated that, the effects of cement on fatigue life of mixes are related to the initial strain level assumed in testing. Finally, based on their laboratory testing results, distinct models were established for different boundary strain levels.

The stabilization of sandy loam clay by using EA as a stabilizer material had investigated [16]. The soil samples were collected from Manuju village, Gowa regency, and South Sulawesi province in Indonesia. It obtained EA type CSS-15 from PT. Widya Sapta Colas. The EA concentrations were 1.5%, 3.0%, and 4.5%. The results of the investigation showed the physical, chemical, and mechanical characteristics of sandy clay loam are improved due to using EA. It was also noticed that chemical bindings occurred among the soil minerals and EA. Finally, plasticity and shear strength of soil increased in a linear relationship with the increase of EA concentration.

2.2 Sulfur Extended Asphalt (SEA)

Attempts to utilize elemental sulfur in asphalt were initiated many years ago. In the early 1938, Bencowitz investigated the use of sulfur in asphalt to improve the properties of asphaltic mixtures. He demonstrated that, stable asphaltic mixtures of 25% by weight of sulfur in asphalt could be prepared by simply stirring the two together in the temperature range of 130°C to 150°C and using the new binder in preparing sulfur-asphalt paving materials [17].

Bacon developed "The Texas Gulf" by basically adding as much as 50% of elemental sulfur in asphalt at 149°C and stirring the mixture vigorously [18].

The optimum sulfur content in sulfur-extended asphalt binders is between 20 and 30 wt%. Below that range, no hardening effect is obtained and above that the improvement of mix workability is reduced [19].

In the 1970s, many laboratory test programs were established to study the effect of sulfur in asphalt mixtures. Also, many field experiments were established to test the performance characteristics of SEA pavements. From 1974 to 1986, the huge majority of published literature on the use of SEA occurred [20].

The feasibility of using dune sand in asphalt-concrete pavement under hot desert climates was conducted [21]. In this study, one-size crushed aggregates were used, also Dense-graded aggregate and powdered sulfur were used in the sand- asphalt mixes. They concluded that, a mixture of dune sand and asphalt is weak, unstable, easily deformed under light loads, and unacceptable for pavement construction in hot regions. The use of powdered sulfur and sand-asphalt mixes reduces the optimum asphalt content, increases considerably the qualities of the mix even under severe environmental conditions, and reduces the pavement thickness.

A field study to compare the performance of SEA to the conventional asphalt pavements was conducted [22]. The results showed that, there was no difference in overall performance between SEA pavement and the conventional pavement.

The optimum sulfur content in sulfur-extended asphalt binders is found somewhere between 20 and 30 wt%. Under the former, no hardening effect is obtained. Above the latter the improvement of mix workability is reduced [19].

King Fahd University of Petroleum and Minerals has conducted major sulfur research in the late 70's and early 80's in cooperation with the Ministry of Transport where sulfur was incorporated in the construction of major road sections, some of which are still functioning. Sulfur is added to asphalt to overcome temperature susceptibility (dependency) of local binders, thereby reducing or eliminating rutting tendency of local mixes.

An extensive laboratory testing program was designed [23], to evaluate improvements in engineering properties of sulfur-asphalt-sand (SAS) mixes in eastern Saudi Arabia. The results, in general, showed improvements in, resilient modulus values Marshall Stability, and reduced permanent deformation of SAS mixes in comparison to usual sand-asphalt mixes.

Use of sulfur as a rejuvenating agent in recycling reclaimed asphalt pavement from a typical failed segment of Dammam Abu Hadriyah Expressway was explored [24]. They indicated that the addition of sulfur, at mixing temperature, would lower the viscosity of the aged asphalt. Upon cooling, recrystallization of sulfur is known to occur, which improves the strength of the mix. Properties like Marshall Stability, resilient modulus and fatigue behavior of sulfur-recycled mix are compared with those of the conventional asphalt-concrete mix. The addition of sulfur results in higher Marshall Stability without significant loss in flow values, higher retained strength index, and higher M_R and tensile strength, indicating superior engineering properties of the recycled mixture over the conventional asphalt hot mix.

Sulfur decrease the resistance to moisture susceptibility in the laboratory and there were minor trends that sulfur may reduce the susceptibility to rutting and increase the susceptibility to fatigue cracking with some mixtures [25].

The main reasons to use additives with bituminous materials could be summarized as follows [26]:

1. To get softer blends at low service temperatures and decrease cracking,
2. To reach stiffer blends at high temperatures and reduce rutting,
3. To increase the stability and the strength of mixtures,
4. To enhance fatigue resistance of blends,
5. To decrease structural thickness of pavements.

The use of sulfur as an additive to extend has been demonstrated successfully in both laboratory tests and fields. Because of the availability and low cost of sulfur, the cost of constructions reduces by as much as 21 percent and binder cost reductions as high as 32 percent are feasible [27].

From spring 2001 through February 2002, about 42 lane miles of roads containing sulfur were built in the southwest United States. These projects incorporated a formed, solid sulfur product that was added directly to existing hot mix plant equipment. Following mixing, the sulfur asphalt was hauled to the project location using conventional dump trucks, road paving, and compaction equipment. An additional 104 lane miles of roads containing sulfur are planned in the southwest U.S., and other road projects incorporating sulfur are also being considered in China, Kazakhstan, and Egypt. The use of a formed, solid material and the direct mixing method minimizes hot asphalt mix plant modifications and associated costs. Also, solid sulfur can be shipped freely without regulation; whereas, liquid sulfur requires special shipping considerations [27].

The expected benefits of the use sulfur extended asphalt were summarized as follows [28]:

1. Decreased cost of hot- mix asphalt (HMA).
2. Saving and conservatory of asphalt binder resources.
3. Comparable pavement performance.
4. Reduced tendency to rut due to the stiffening effect of sulfur on asphalt.

The performance of sulfur-modified mixtures in the laboratory was studied [29]. Rutting performance of the prepared mixtures was evaluated using the asphalt pavement analyzer (APA) test at 58°C, and the mixture stiffness modulus was measured at a temperature ranging from 10 to 30°C. Additionally, the low temperature performance was evaluated by using the Thermal Stress Restraining Specimen Test (TSRST). The results of this study showed that the rutting resistance and stiffness modulus of the mixture are improved. In addition, the modified sulfur additive improved the elongation properties of the mix at low temperatures.

A complete experimental program to investigate the moisture resistance and dynamic modulus of sulfur-modified asphalt mixtures had conducted [20]. Results indicated that sulfur-modified asphalt mixture had a lower tensile-strength ratio (TSR) after curing, but greater dynamic module for all combinations of test temperatures and frequencies.

Feasibility of using sulfur as an additive for local asphalt concrete mixtures at KFUPM was investigated [30]. They also many cases of using sulfur modified asphalt in road construction including the field trial at Khursaniyah and the concerns related to air pollution due to sulfur containing gases were studied. Sulfur-asphalt concrete consists of testing local sulfur; Shell Canada sulfur-extended asphalt modifier (SEAMTM), with local asphalt-concrete mixes was studied to assess the effect of sulfur and modified sulfur materials by comparing the performance of these paving mixes. Based on laboratory and field trials results, they reported that SEAMTM and sulfur modified asphalt concrete can be produced, hauled, placed and compacted easily with conventional methods and equipment.

30% replacement of asphalt with sulfur is the optimum replacement. Based on the lab study and four years of monitoring, sulfur asphalt outperformed conventional asphalt and polymer modified asphalt in terms of rutting resistance [31].

The effects of sulfur-modified warm mix asphalt (WMA) on the predicted performance from the Mechanistic-Empirical Pavement Design Guide (MEPDG) and assessed the life cycle costs of pavement structures constructed with this sustainable alternative had studied [32]. To achieve this objective, three typical pavement structures were analyzed at three traffic levels (low, medium, and high). Based on the results of the analysis, the use of sulfur-modified WMA improved the predicted rutting and fatigue performances and the overall pavement service lives over conventional mixtures at all traffic levels. The results also showed that sulfur modification has the potential to decrease production and life cycle costs when compared to a conventional asphalt mixture made with the same binder grade. Also the laboratory mechanistic properties of sulfur-modified warm-mix asphalt (WMA) with conventional asphalt mixtures was compared [32], three mixtures, two hot-mix asphalt (HMA) and one WMA were prepared. Mixture one used an unmodified asphalt binder classified as PG 64-22, Mixture Two used a styrene-butadiene-styrene elastomeric modified binder classified as PG 70-22, and Mixture Three was a WMA that incorporated a sulfur-based mix additive and a PG 64-22 binder. A suite of tests was performed to evaluate the rutting performance, moisture resistance, fatigue endurance, fracture resistance, and thermal cracking resistance of the three mixtures. Results of the experimental program showed that the rutting performance of sulfur-modified WMA was comparable or superior to conventional mixes prepared with polymer-modified and unmodified asphalt binders. Results of the modified Lottman test showed that the moisture resistance of the sulfur-modified mixture was comparable to conventional mixes. Results of the fracture tests showed that sulfur-modified WMA is more susceptible to cracking than conventional mixes, given its stiff characteristics. However, given these stiff properties, the higher modulus of sulfur-modified mixtures will reduce the magnitude of strain induced in the pavement. Thermal stress restrained specimen test results showed that the sulfur-modified WMA had greater fracture stress than the polymer-modified mixture.

2.3 Permanent Deformation

"*Rutting is defined as the formation of twin longitudinal depression along the wheel paths mainly caused by progressive movement of materials due to repeated loading*." [33].

There are several wheel path rutting classifications, the famous one of which was provided in 1979 by the Federal Highway Administration, which classified rutting into three levels of severity [34] :

1. Low, from 6 to 12.5 mm (0.25 to 0.5 inches),
2. Medium, from 12.5 to 25 mm (0.5 to 1.0 inches), and
3. High, over 25 mm (1 inch).

A rut depth of 12.5 mm (0.5 inch) is typically accepted as the maximum allowable rut depth [34, 35].

2.3.1 Rutting Model Review

A resilient response is important for the load-carrying ability of the pavement and a permanent strain response which characterizes the long-term performance of the pavement and the rutting phenomenon. Figure 2.1 gives a simple illustration of resilient and permanent strains in granular materials during one cycle of load application [36].

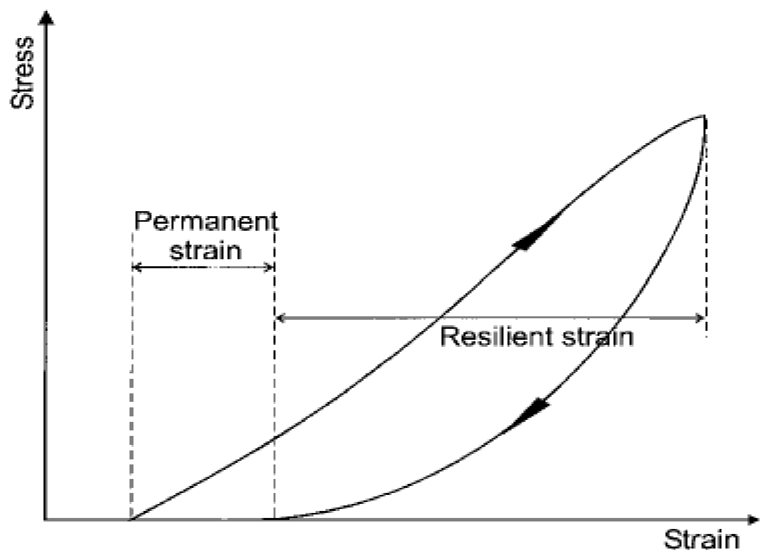


Figure 2.1: Strains in Granular Materials during One Cycle [37].

Barksdale's model (1972) as one of the earliest permanent deformation models developed for unbound pavement materials [38], suggests that the accumulation of permanent deformation is linearly increased with the logarithm of the number of load repetitions:

$$\varepsilon_p = a + b \log(N) \quad (2.1)$$

Where:

ε_p = Accumulated axial permanent strain at cycle N;

a, b = Regression constants; and

N = Number of load cycles.

A log-log relationship between the permanent strain and number of load repetition was studied [39], and follows equation was suggested:

$$\varepsilon_p = aN^b \quad (2.2)$$

Where:

ε_p: Accumulated Permanent Strain at N cycle,

N: Number of Load Repetitions, and

a,b: Non-linear Regression Coefficients.

This classic power equation is derived from the secondary stage in a typical behavior of HMA tested sample under repetitive loads as shown in Figure 2.2, where “a” is the intercept at N = 1 cycle and “b” is the slope of the line.

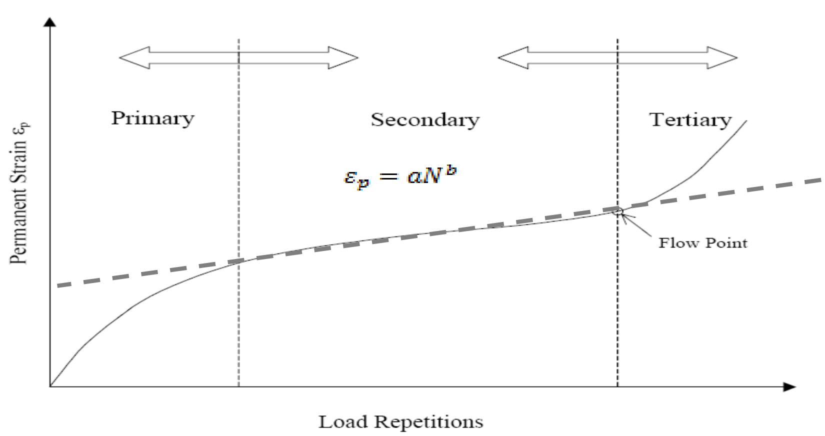


Figure 2.2: Typical Permanent Deformation Behaviors for HMA under Repetitive[37]

Allen and Deen [40], proposed for any layer, the following formulation:

$$\log(\varepsilon_p) = C_o + C_1(\log(N)) + C_2(\log(N))^2 + C_3(\log(N))^3 \quad (2.3)$$

Where: ε_p =permanent axial strain, N = number of load applications, C0, C1, C2, C3 =coefficients depending on the type of material

The NCHRP 1-37A [41], design methodology characterizes the permanent deformation behavior of unbound base, sub-base, and sub-grade materials using a model based on work by Tseng [42]: they developed a permanent deformation model based on the statistical analysis of a database of cyclic triaxial test results:

$$\varepsilon_p = \frac{\varepsilon_a}{\varepsilon_r} e^{-\left(\frac{\rho}{N}\right)^{\beta}} \varepsilon_v h \quad (2.4)$$

Where:

ε_a = permanent strain,

εr = resilient strain imposed in laboratory test,

εv = average vertical resilient strain in the layer,

ε_0, β, ρ = material parameters,

N = number of load applications, and

h = layer thickness .

Thomason [43], investigated the rutting behavior of different UGB materials under cyclic loading and found that the accumulation of permanent strain followed a linear relationship with the logarithm of the number of load cycles. They proposed the following formulation:

$$\varepsilon_p = a + b\log(N) \quad (2.5)$$

Where:

εp = Accumulated axial permanent strain at cycle N;

a, b = Regression constants; and

N = Number of load cycles.

Sweere [44] found that Barksdale's model failed to fit test results with a large number of load cycles and suggested that a log-log expression was more appropriate:

$$\log(\varepsilon_p) = a + b \log(N) \tag{2.6}$$

For VESYS model, when axial repeated load creep test is conducted to determine the resilient strain, resilient modulus, and permanent deformation [45].

$$\varepsilon_p = \mu \varepsilon_r N^{-\alpha} \tag{2.7}$$

Where:

ε_p = the permanent or plastic strain due to a single load application,

μ = a permanent deformation parameter representing the constant of proportionality between permanent strain and elastic strain,

ε_r = resilient strain,

N = load applications,

α = a permanent deformation parameter indicating the rate of decrease in the rutting parameters. The μ and α, are defined by:

$$\mu = \frac{ab}{\varepsilon_r} \quad , \quad \alpha = 1 - b \tag{2.8}$$

Thomason study [46] recommended the use of the permanent strain accumulation model developed at Ohio State University. This strain model predicts total rutting, considers the rutting rate of the pavement as indicated by the following equation:

$$\frac{\varepsilon_p}{N} = AN^m \quad (2.9)$$

Where: ε_p = permanent strain,

N = number of load application,

A = Experimental constant (depends on material type and stress state), and

m= Experimental constant (depends on material type)

The equation above is valid for describing the progression of rutting in pavement layers, asphalt surface and base courses, granular base and sub-base courses, and sub-grade soils. For unbound granular materials the typical stress levels found in pavement foundations, permanent axial strains stabilize after a large number of load cycles (about 10^5). They obtained good predictions with the following relationship, which assumes that ε_{1p} has a finite limit for an infinite number of cycles [47]:

$$(\varepsilon_p) = A\left(1 - \left(\frac{N}{100}\right)^{-B}\right) \quad (2.10)$$

A permanent deformation model based on the results of accelerated testing using a heavy vehicle simulator (HVS) was developed [48], for the pavement sub-grade:

$$\varepsilon_p = N^s e^c\left(e^{\beta\sigma_c} - 1\right) \quad (2.11)$$

Where: ε_p = permanent deformation,

N=number of load repetitions,

σc = vertical compressive stress on top of the subgrade and

c, s, B = regression parameters

The standard for the repeated load triaxial test suggests the following equation to relate permanent axial deformation with the number of cycles N [49] :

$$(\varepsilon_p) = \varepsilon_p(100) + A\left(1 - \left(\frac{N}{100}\right)^{-B}\right) \qquad (2.12)$$

Where ε_p = permanent strain,

N = number of load application, and

A, and B are parameters with positive values.

A summary of various relationships, proposed by different authors is presented in Table 2.1.

Table 2.1: Relationships describing the variation of permanent axial deformations with the number of load cycles [47].

Author	relationship	Parameters
Barksdale [1972]	$\varepsilon_1^p = a + b\log(N)$	a, b
Khedr [1985]	$\frac{\varepsilon_1^p}{N} = A.N^{-b}$	A,b
Paute and al [1988]	$\varepsilon_1^{p^*} = \frac{A\sqrt{N}}{\sqrt{N}+D}$	$\varepsilon_1^{p^*}$ permanent deformation after the first 100 cycles A parameter function of stress level, D
Sweere [1990]	$\varepsilon_1^p = a\,N^b$	a, b
Hornych and al. [1993]	$\varepsilon_1^{p^*} = A\left(1 - \left(\frac{N}{100}\right)^{-B}\right)$	$\varepsilon_1^{p^*}$ permanent axial strain after the first 100 cycles A, B
Vuong [1994]	$\varepsilon_1^p = \varepsilon_1^r\left(\frac{a}{b}\right)N^c$	ε_1^r resilient axial strain a, b, c
Wolff and Visser [1994]	$\varepsilon_1^p = (c\,N + a)(1 - e^{-b\,N})$	a, b, c
Huurman [1997]	$\varepsilon_1^P(N) = A.(\frac{N}{1000})^B + C.(e^{D\frac{N}{1000}} - 1)$	A, B, C, D parameters function of the level of stress

CHAPTER 3

METHODOLOGY

The marl, sabkha, and dune sand are the main focus of this work; different test samples were prepared from these soils with ESA and EA. These blends are tested in accordance with ASTM [50] and The American Association of State Highway and Transportation Officials [51]. A statistical analysis has been utilized in order to study the effects of different factors (i.e., ESA and EA contents) on the strength of soils. All the statistical evaluations were conducted using Minitab statistical application software [52].

The flow chart of the research program for this study is shown in Figure 3.1, which consists of five phases, as follows:

1. Soils selection and characterization.
2. Selection and characterization of EA and ESA.
3. EA and ESA mix design.
4. Designed mixes evaluation, and
5. Data analysis and modeling.

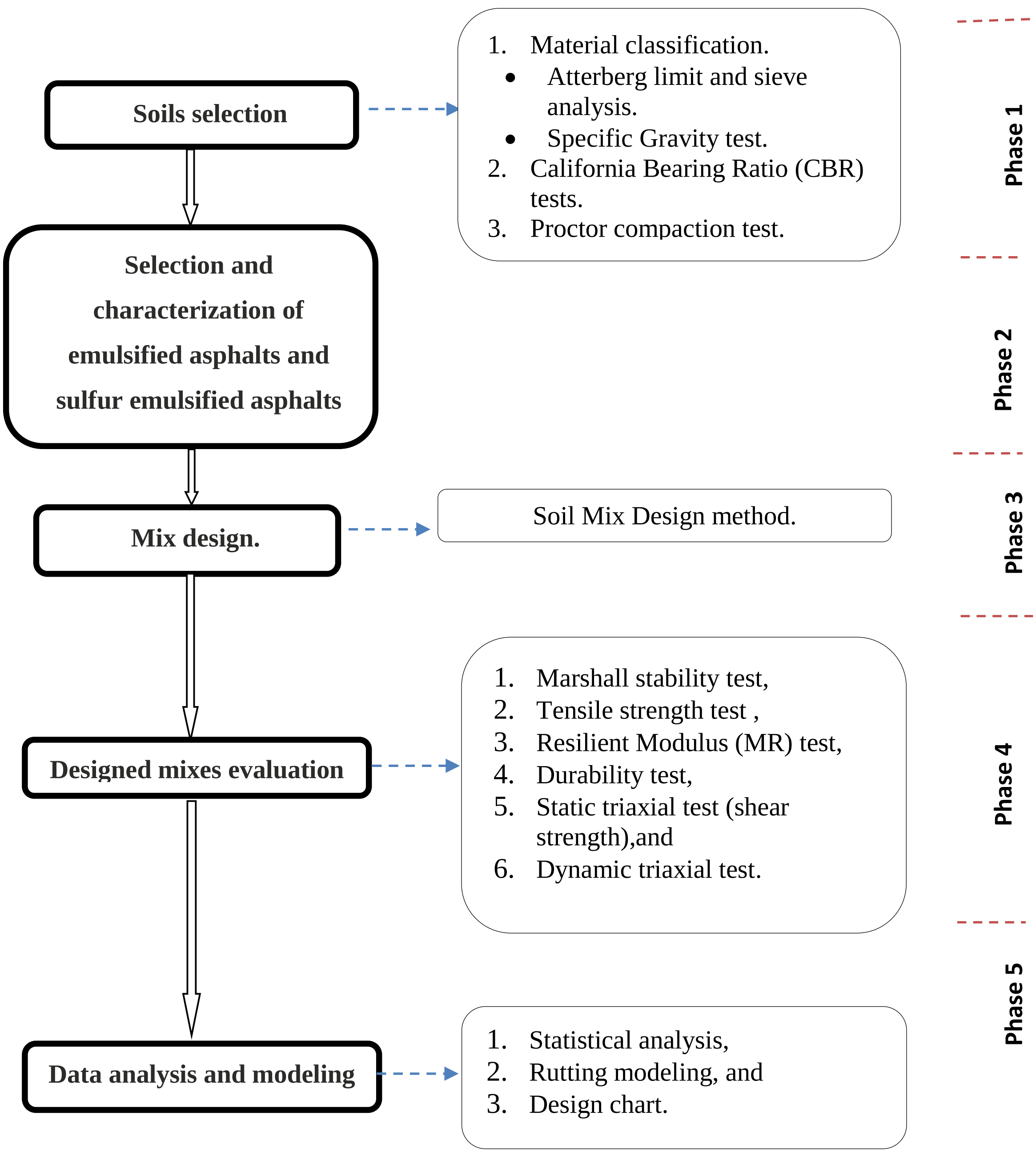


Figure 3.1 : Work flow chart

3.1 Soils Selection

Three types of soils were selected for this study: dune sand, non-plastic marl, and sabkha. The sabkha was collected from Al-Aziziyah zone, which is located 10km south of Dhahran, Saudi Arabia. Marl and dune sand were chosen due to their abundance at low cost in Saudi Arabia and were collected from Dhahran city. We selected these soils due to their availability in most of the areas of the Eastern region of Saudi Arabia, where the good quality soils are rare.

3.1.1 Physical Property

Physical property tests were performed to investigate the probable treatment of these soils and their use in the construction of road projects. These physical tests included Liquid Limit and Plastic Limit ASTM D4318, Specific Gravity, ASTM D854, Relative Density tests ASTM D4254 and ASTM D 4253 and grain size distribution, ASTM D422. The compaction and strength characteristics were investigated by using modified Proctor compaction, ASTM D1557 and California bearing ratio tests, ASTM D1883.

3.1.2 Emulsified Asphalt (EA)

The EA used in this study is the only locally available grade CSS-1h, obtained from SANDFIX Company.

3.1.3 Emulsified Sulfur Asphalt (ESA)

The ESA was produced using the laboratory Emulsified Asphalt plant available in KFUPM laboratory. For the production of emulsified sulfur asphalt, the sulfur was heated to melt and then mixed with hot ordinary asphalt before placing in an emulsified asphalt plant.

Afterwards, the mixed sulfur asphalt was mixed with water and emulsifying agent using high shear mixer.

3.2 Experimental Design

The experiment was designed to characterize and evaluate the behavior of three soils: marl, sabkha and dune sand under field conditions with two types of binders i.e. EA and ESA. The tests were carried out at temperatures of 22°C and 40°C and included the following:

1. Marshall stability (ASTM D 1559),
2. Indirect Tensile Strength (ASTM D 4867),
3. Resilient Modulus (M_R) (AASHTO T-307),
4. Static Triaxial (ASTM D2850) and
5. Dynamic Triaxial (AASHTO T-307).

Marshall Stability, Indirect Tensile Strength, and Static Triaxial tests were carried out at 22°C while, Resilient Modulus and Dynamic Triaxial tests were carried out at 22°C and 40°C. All tests were done following ASTM [50], and AASHTO Standards [51]. The experimental design is shown in Table 3.1.

Table 3.1: Experimental Design.

<table>
<tr><th>Soil</th><th>Test</th><th>Test Temperature °C</th><th>EA %</th><th>ESA %</th></tr>
<tr><td rowspan="5">Sabkha , Dune sand and Marl</td><td>Marshal Stability</td><td>22</td><td rowspan="2">3 to 18</td><td rowspan="2">3 to 18</td></tr>
<tr><td>Indirect tensile strength</td><td>22</td></tr>
<tr><td>Static triaxial</td><td>22</td><td rowspan="3">At Optimum</td><td rowspan="3">At Optimum</td></tr>
<tr><td>Resilient modulus</td><td>22&40</td></tr>
<tr><td>Dynamic triaxial</td><td>22&40</td></tr>
</table>

3.3 Statistical Analyses

The data generated from all tests were subjected to statistical scrutiny via analysis of variance (ANOVA) using Minitab (version 16) software [52]. The effect of EA and ESA as additive material in the soil mixes, were statistically analyzed using the data obtained from the different tests performed on modified mixes.

The experimental design for marshal stability and indirect tensile strength involve one factor (additive type EA or ESA).

For dynamic triaxial test, the hypothesis tested using general Lanier models (a three-factor analysis of variance (ANOVA). The three factors were additive type, Deviator stress, and temperature. Finally, for resilient modulus test, the hypothesis also tested using general Lanier models, but number of factors was four (additive type, Deviator stress, confining stress and temperature).

All factors were statistically tested for the null hypothesis "Ho: The data obtained has equal means". Null hypothesis is rejected at 95% confidence level if P-value is less than or equal to 0.05.

3.4 Emulsified Asphalt and Emulsified Sulfur Asphalt Mix Design

The purpose of the mix design is to find the optimum emulsified asphalt and optimum emulsified sulfur asphalt. Cold Mixture Design method, according to Basic Asphalt Emulsion Manual (BAEM) [53] , was used for mixing the EA or ESA with soil. This method based on research conducted at the University of Illinois using a modified Marshall method of mixed design and a moisture durability test.

It was used to determine the optimum EA and ESA content for dune sand, marl and sabkha. Mix trials were made for different emulsion ranges (3% to 18% of dry soil's weight). Water addition varied between 1% and 5%. A 2% Portland cement was added for early curing. Materials added in the following order: soil, water, cement and asphalt. Mixing time was limited to 30 seconds to avoid stripping problem. The produced mix was compacted using the Marshall compactor; where 75 blows applied to each side.

3.5 Mixes Evaluation

The major properties of concern in stabilizing pavements are stability and durability. Stability is the resistance to deformation and flow while durability refers to the resistance to the effects of weather or its combination with other forces.

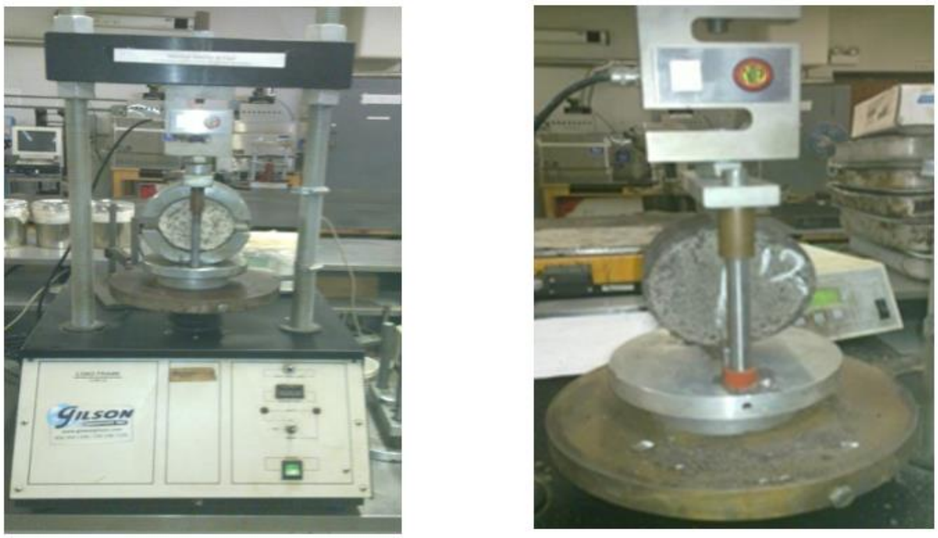
3.5.1 Marshall Stability and Durability Test, ASTM D 1559

The objective of this test is to determine the stability and durability using the Marshall apparatus shown in Figure 3.3. The durability is then determined as the ratio of the Marshall stability of the soaked Marshall Stability to the standard (dry) Marshall Stability.

Figure 3.2: Marshall Samples

3.5.2 Indirect Tensile Strength (ITS) Test, ASTM D 4867

The ITS test provides tensile strength that is useful in characterizing mixtures. Tensile strength is often used in evaluating water susceptibility of mixtures which is also sometimes used to help evaluate cracking potential of a bituminous mixture.



a) Marshal Apparatus

b) ITS Apparatus

Figure 3.3: Marshal and ITS Apparatus.

3.5.3 Resilient Modulus Test, AASHTO T-307

Dynamic resilient modulus was measured using the dynamic triaxial test at 22°C and 40°C. Table 3.2 presents the loading sequences and conditioning requirement for testing samples. The repeated load triaxial test system employed in the study is shown in Figure 3.4. Repeated load duration of 0.1 sec was chosen in the study for a typical highway loading with a simulated speed of 65 kph.

Figure 3.4: Resilient Modulus test setup

Table 3.2: Loading Sequence for Resilient Modulus Test, AASHTO T-307 [54]

Combination	Confining Pressure (kPa)	Deviator Stress (kPa)
0	103.4	137.9
1	20.7	34.5
2		48.3
3		62.0
4	34.5	34.5
5		68.9
6		103.4
7	68.9	34.5
8		68.9
9		137.9
10		206.8
11	103.4	68.9
12		137.9
13		206.8
14		175.76
15	137.9	10.0
16		15.0
17		20.0
18		30.0
19		40.0

3.5.4 Static Triaxial Shear Strength, ASTM D 2850

The results from this test are used to estimate mixed soils modulus, Mohr-Coulomb failure envelope, and mixed soil strength parameters (angle of internal friction and cohesion intercept). Figure 3.5 shows the static test setup where stabilized soil sample is subjected to a static confining pressure and a deviator stress that is gradually increased at a strain rate of 1.0 per min at a temperature of 22°C till the sample fails due to shear.

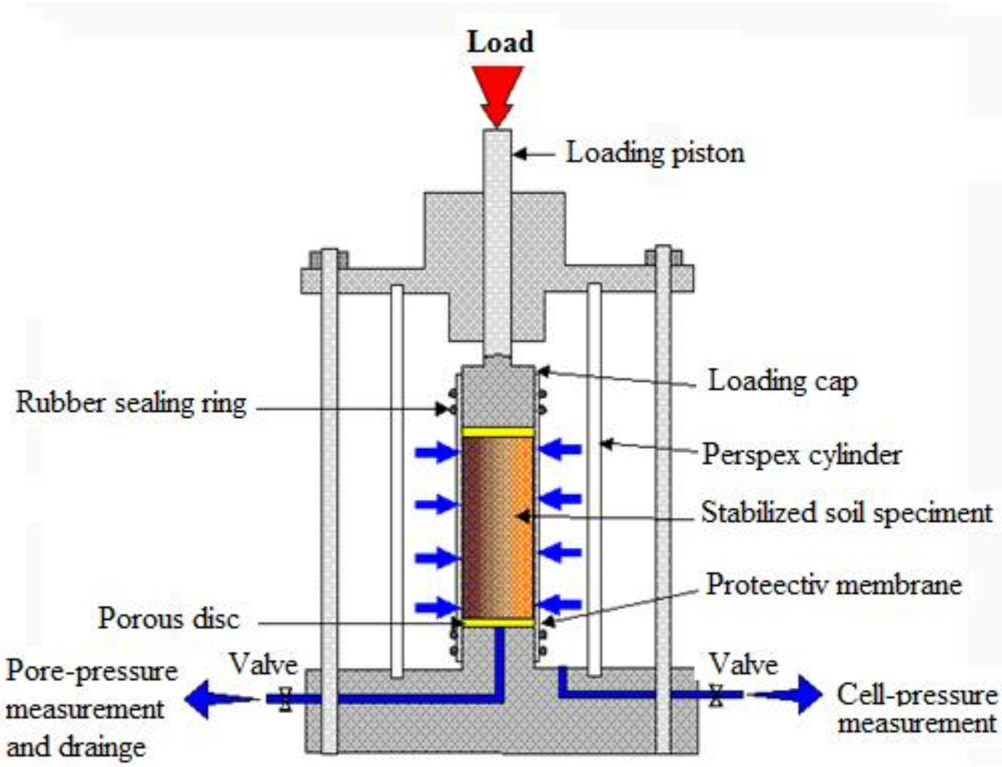


Figure 3.5: Static triaxial test setup.

3.5.5 Dynamic Triaxial Test, AASHTO T-307

A cylindrical sample is subjected to 68.8 kPa confining pressure and variable levels of deviator stress (137.8, 275.7, 413.4, 482.5, and 551.5 kPa) to simulate the traffic loading that the base and sub-base materials are subjected to the road.

Figure 3.6 shows the repeated triaxial load test setup. The test was conducted at 20^{o}C and at 40^{o}C using loading cycles of 0.1 sec loading period and a 0.9 sec unloading period. Permanent deformation response for EA and ESA asphalt mixes were characterized using repeated load test on specimens that have the same size that was used for resilient modulus test (101.6mm diameter by 203.2mm height).

Figure 3.6: Dynamic Triaxial Sample Setup

CHAPTER 4

RESULTS AND DISCUSSION

The results for all tests will be discussed for each test separately. Soil characterization, the Marshal Stability, the Indirect Tensile Strength, and the Resilient Modulus tests results were examined. Afterwards, the Static triaxial test was discussed and finally, the dynamic triaxial test result was analyzed.

4.1 Soil Physical Properties

All tests performed on each soil along with the test designations from ASTM Specifications [50], and AASHTO [51]. These tests were concerned mainly with the identification of basic physical properties of the materials to be used in mix design. marl, sabkha, and dune sand were classified as non-plastic because it was difficult to get the required number of blows for the liquid limit test, in addition, it could not be rolled to a thread of 3.18mm plastic limit test; as a result, the liquid limit and plastic limit are reported as nil.

The grain-size distribution curves are presented in Figure 4.1 to Figure 4.3, it can be seen that sabkha could be classified as SP-SM according to the Unified Soil Classification System (USCSP) [50]. However, according to the AASHTO [51], soil classification system, the soil can be classified as A-3 based on both dry and washed sieving. Similarity, in Figure 4.2, marl can be classified as SM according to the USCS system. However, according to the AASHTO soil classification system, the soil can be classified as A-3 based on dry sieving. Finally, in Figure 4.3, dune sand can be classified as SP according to the

USCS system. However, according to the AASHTO soil classification system, the soil can be classified as A-3 based on dry sieving. Table 4.1 shows the summary of all soil tests.

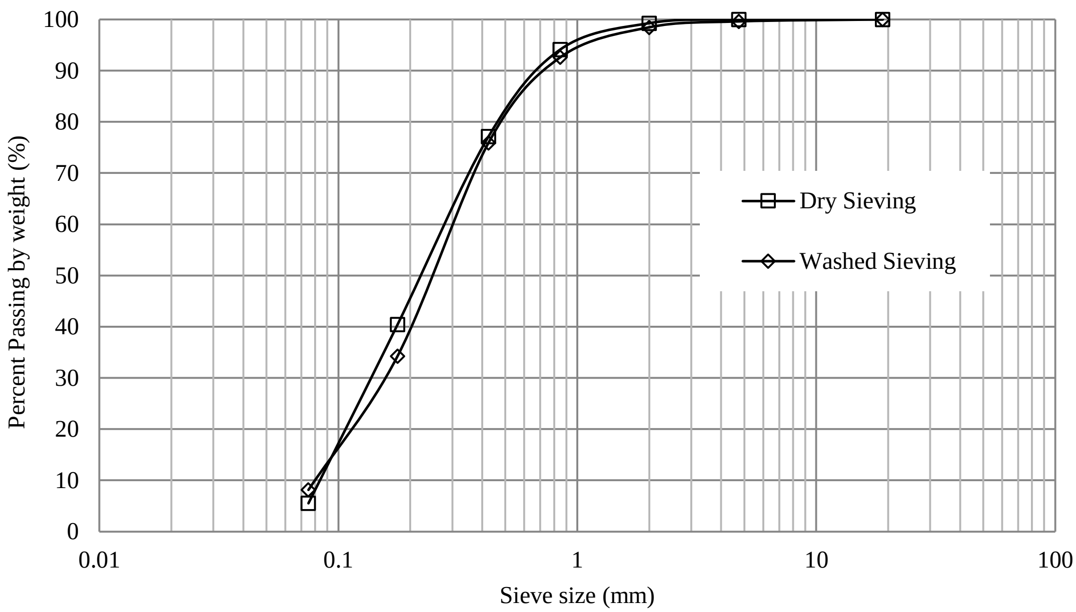


Figure 4.1: Sabkha grain size distribution

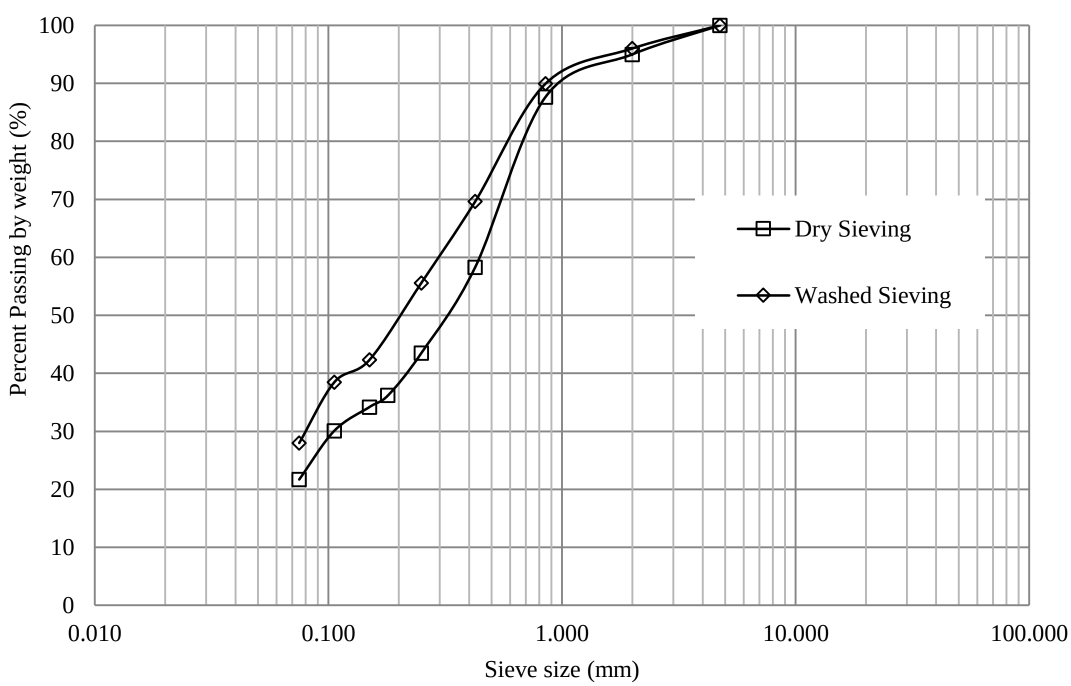


Figure 4.2: Marl grain size distribution

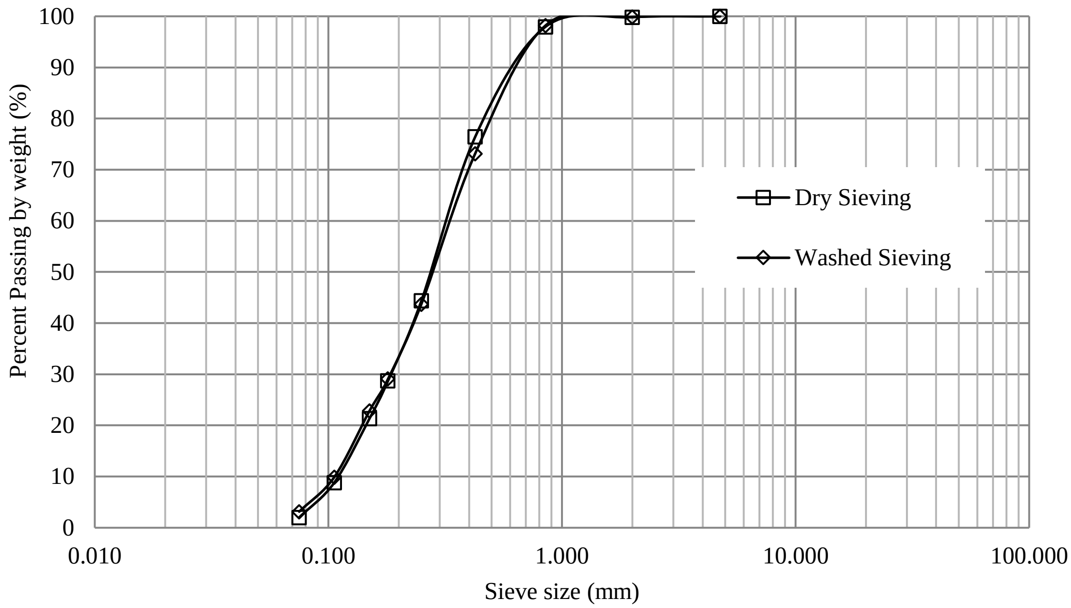


Figure 4.3: Dune sand grain size distribution

Table 4.1: Soils Physical Properties.

Test type	Marl	Dune sand	Sabkha
Specific Gravity	2.68	2.63	2.47
Dry Density, kN/m^3	18.4	---	17.1
Optimum Water content, %	13	9	12
Minimum density	---	1.63	---
Maximum density	---	1.84	---
California Bearing Ratio (CBR), %	25	15	10
AASHTO USCS system	A-1-b SM	A-3 SP	A-3 SP-SM

4.2 Marshal Stability

Marshal Stability test results of marl, sabkha, and dune sand were studied according to the treatment by EA and ESA.

The comparison between dry and soaked stability curves for marl, sabkha, and dune sand are presented in Figure 4.4, 4.5, and 4.6 respectively.

For EA mixes, test results indicate that the maximum dry and soaked stability for marl were 33kN and 29.4kN respectively at the Optimum Residual Asphalt Content (ORAC) was 8%, while the maximum dry and soaked stability for sabkha were 12.5kN and 7.5kN at ORAC of 4%. Similarly for dune sand, the maximum dry and soaked stability were 12kN and 7kN at ORAC of 5.4%.

Also, these Figures indicate, for ESA mixes, the maximum dry and soaked stability for marl were 22.4kN and 19.8kN respectively, at the ORAC was 7.2 %, while the maximum dry and soaked stability for sabkha were 10.6kN and 6.8kN at ORAC of 3.6 %. Similarly for dune sand, the maximum dry and soaked stability were 9.8kN and 5.8kN at percent residual asphalt content of 5.4 %.

The results of stability show that the dry stability curves were consistently above soaked stability due to water effect. Water can cause loss of cohesion (strength) of asphalt and destroys the adhesion bond between the asphalt and the soils in the mixture.

Marl produced a higher stability (dry and soaked) relative to the soil materials and the stability of the sabkha stabilized Marshall Specimens was found to be higher than that of the dune sand. Although, all Marshall Stability results were found to exceed the minimum required Marshall Stability (6.6 kN) except soaked marshal stability for dune sand [53]. Furthermore, the figures clearly show that residual asphalt addition led to an increase in the stability until it reached the maximum stability value. After that, further increase in the residual asphalt resulted reduction in stability value.

Dry and soaked stability for EA mixes were higher than that for ESA mixes, this is due to the fact that moisture reduce stability of sulfur – asphalt mixes. Summary of results for marshal stability are presented in Table 4.2.

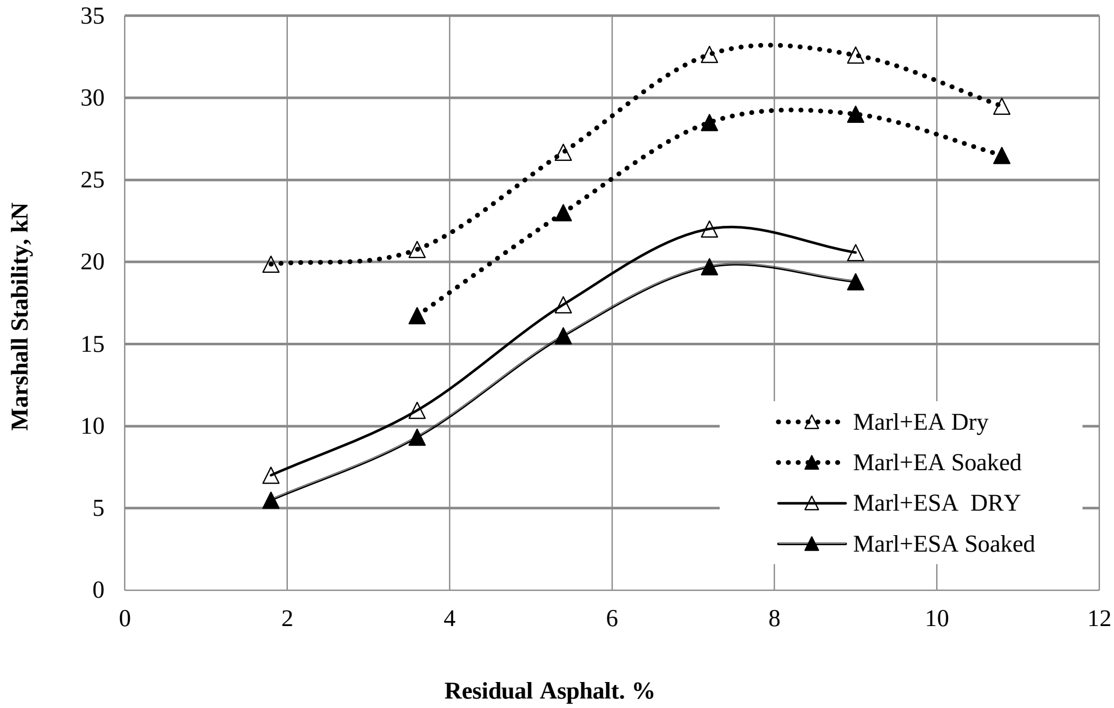


Figure 4.4: Dry and soaked stability vs. residual asphalt content of EA and ESA Marl mixes.

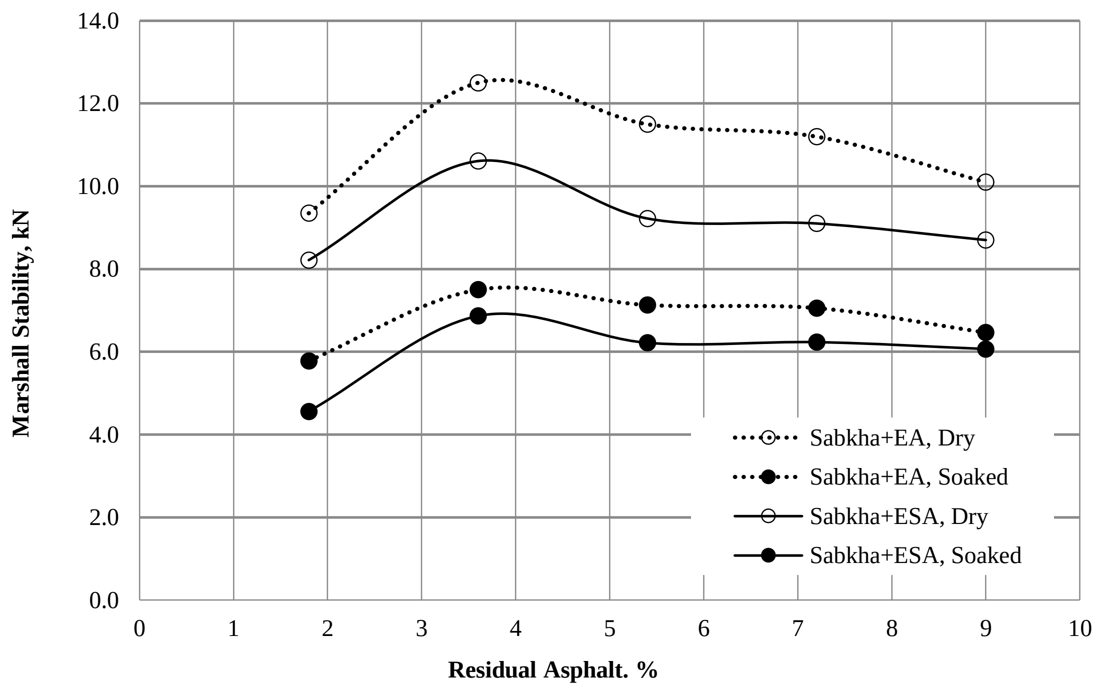


Figure 4.5: Dry and soaked stability vs. residual asphalt content of EA and ESA sabkha mixes.

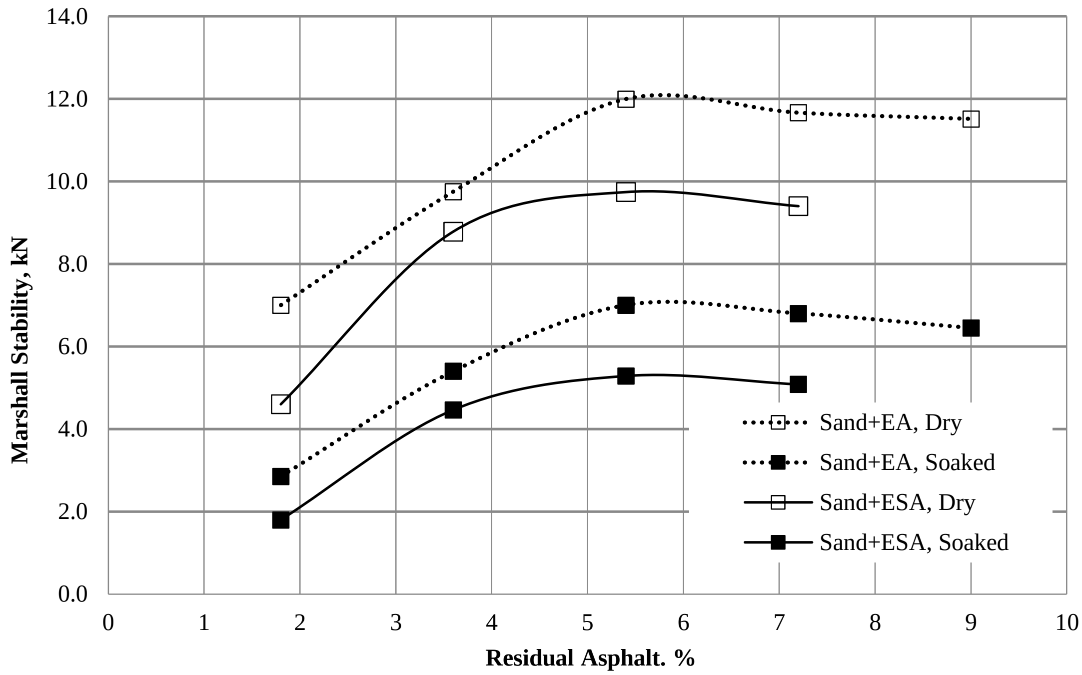


Figure 4.6: Dry and soaked stability vs. residual asphalt content of EA and ESA dune sand mixes.

Table 4.2: Summary of results for marshal stability

Soil type	Type of additive	ORAC%	Dry Stability (kN)	Soaked Stability (kN)	Minimum Stability (kN) [53]
Marl	EA	8.0	33.0	29.4	6.6
	ESA	7.2	22.4	19.8	
Sabkha	EA	4.0	12.5	7.50	
	ESA	3.6	10.6	6.80	
Dune sand	EA	5.4	12.0	7.00	
	ESA	5.4	9.80	5.30	

The results of obtained durability are shown in Figure 4.7 which indicate that marl, sabkha and dune sand mixes at ORAC have more than 50% retained durability (minimum durability 50% [53]). Durability in general increases with an increase in the percent residual asphalt content. Furthermore, marl mixes have a higher durability relative to the other soils, and the durability of the sabkha mixes were found to be higher than that of the dune sand mixes.

As, observed from the Figure 4.7, EA blends show lower durability compared to their ESA blend for marl and sabkha.

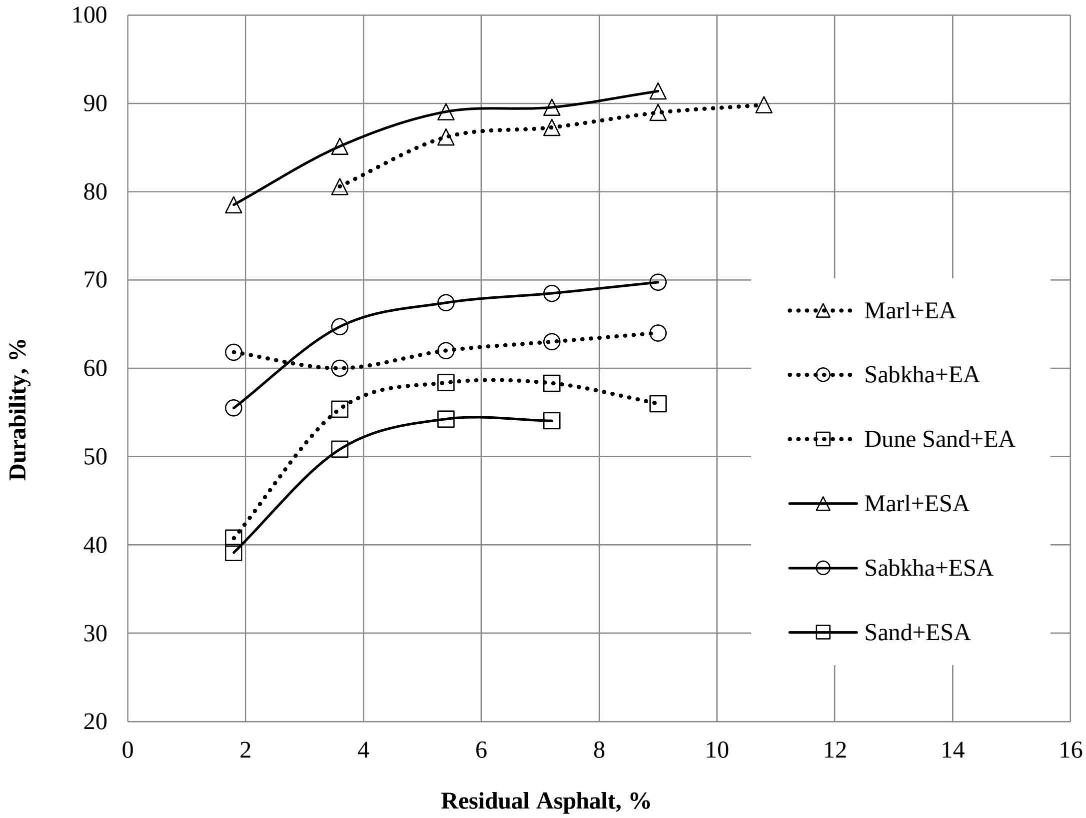


Figure 4.7: Durability vs., residual asphalt content of EA and ESA soil mixes.

Inverse relationship of water absorption was found with binder content in Figure 4.8. As expected, when the residual asphalt content increased, the water absorption decreased because more bitumen fill voids and reduce water absorption moreover, porosity reduces and the bitumen film thickness coating the mineral aggregates increases causing a reduction in permeability and improved protection against water damage. It is worth mentioning that typically a maximum allowable value for the water absorption is 4%.[53]. Summary of results for durability and water absorption are presented in Table 4.3.

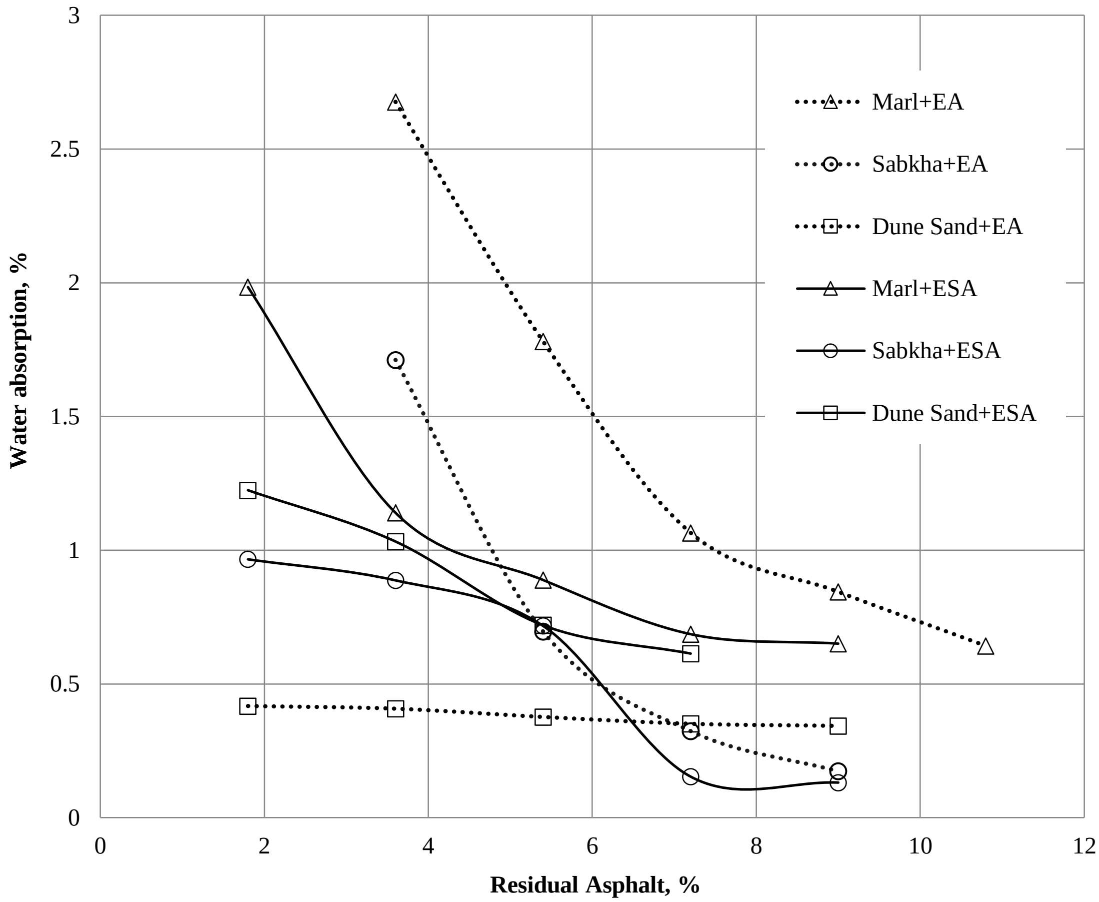


Figure 4.8: Water Absorption vs, residual asphalt content of EA and ESA soil mixes.

Table 4.3: summary of results for durability and water absorption.

Soil type	Type of additive	ORAC%	Water absorption %	Maximum Water absorption %	Durability %	Minimum Durability % [53]
Marl	EA	8.0	0.80	4	90	50
	ESA	7.2	0.68		91	
Sabkha	EA	4.0	1.30		60	
	ESA	3.6	0.88		65	
Dune sand	EA	5.4	0.37		85	
	ESA	5.4	0.71		54	

Note: Three replicates of each sample were tested for each cell.

The Analysis of variance (ANOVA) analysis of Marshall dry stability test shows that additive type has a significant effect on stability for all types of soil (i.e., the P-value, was less than of 0.05) as can be seen from Table 4.4. This means that the usage of EA or ESA causes a different and considerable change in the soil stability.

For soaked stability, the behavior was different. As it can be observed from Table 4.5, the effect of additive type on the soaked stability was insignificant (i.e., the F-value was more than 0.05) for sabkha and dune sand, whereas for marl, the treatment type showed significant effect on the soaked stability.

Table 4.4: Result of Dry Marshal Stability ANOVA at 5% significance level.

	Factors/Additives	Calculated F_{value}	P-value	Comment
Marl	Type of additives EA or ESA	372.23	0.000	Significant
Sabkha	Type of additives EA or ESA	19.74	0.011	Significant
Dune sand	Type of additives EA or ESA	14.2	0.020	Significant

Table 4.5: Result of Soaked Marshal Stability ANOVA at 5% significance level.

	Factors/Additives	Calculated F_{value}	P-value	Comment
Marl	Type of additives EA or ESA	136.11	0.000	Significant
Sabkha	Type of additives EA or ESA	0.180	0.694	Insignificant
Dune sand	Type of additives EA or ESA	4.400	0.104	Insignificant

4.3 Indirect Tensile Strength (ITS).

The ITS of the marl, sabkha, and dune sand were studied according to treatment type (EA and ESA).

The relationship between ITS and percent residual asphalt content for the stabilized marl, dune sand and sabkha with EA and ESA, is presented in Figure 4.9

From Figure 4.9, it can be seen that the ITS values have increased with an increase in the percent residual asphalt content when it reached at the maximum ITS value. After that, further increase in the percent residual asphalt content resulted in a reduction in the ITS value. Also, the marl mixes produced a higher ITS value relative to the other soil whereas, the ITS value of sabkha mixes were found to be higher than that of dune sand mixes.

Although ITS results for marl and sabkha with EA and ESA at ORAC satisfied the recommended requirements of 200 kPs [53], but the ITS for dune sand mixes did not satisfy the minimum requirement of ITS.

The test results indicated that for EA mixes, the maximum ITS value for marl was 615 kPa at the ORAC of 8% whilst, the maximum ITS value for sabkha was 233 kPa at ORAC of 4%. Similarly, for dune sand, the maximum ITS value was 163 kN at ORAC of 5.4%. Figure 4.9 indicates that for ESA mixes, the maximum ITS for marl was 617 kPa at the ORAC of 7.2% whilst, the maximum ITS value for sabkha was 270 kPa at ORAC of 3.6%. Similarly for dune sand, the maximum ITS value was 106 kN at ORAC of 5.4%. Summary of results for ITS is presented in Table 4.6.

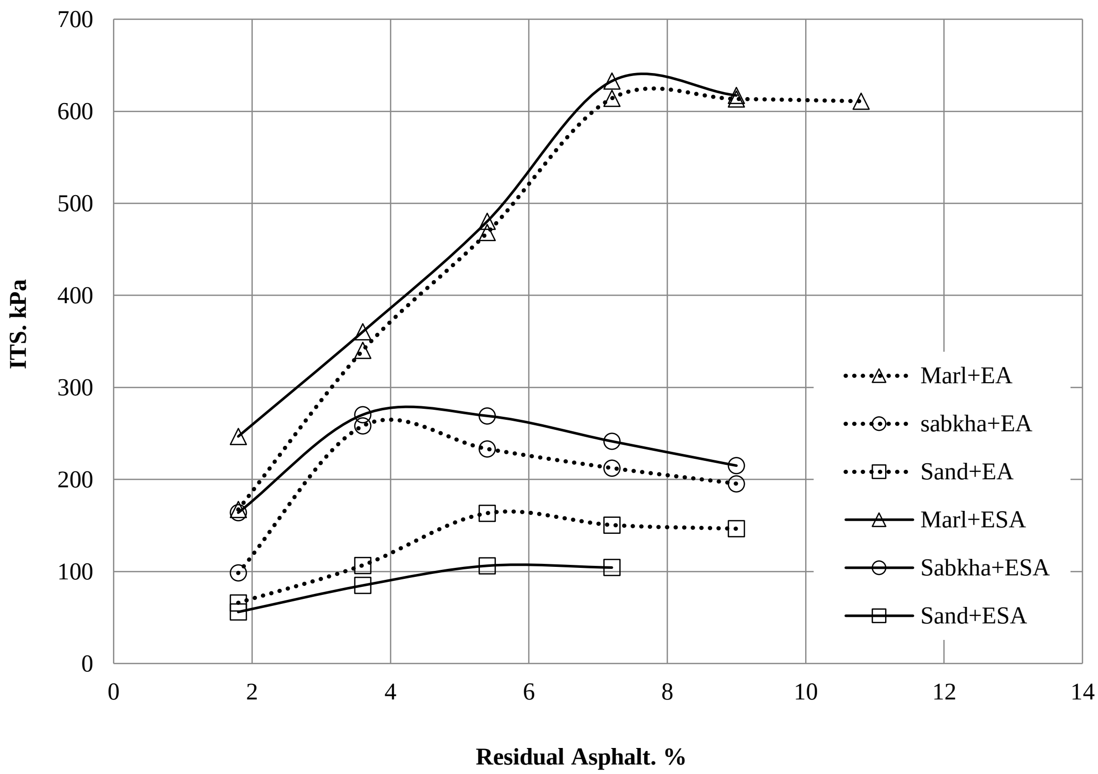


Figure 4.9: ITS vs, residual asphalt content of EA and ESA soil mixes.

Table 4.6: summary of results for indirect tensile strength

Soil type	Type of additive	ORAC%	ITS (kPa)	Minimum ITS (kPa) [53]
Marl	EA	8.0	615	6.6
	ESA	7.2	617	
Sabkha	EA	4.0	233	
	ESA	3.6	270	
Dune sand	EA	5.4	163	
	ESA	5.4	106	

Note: Three replicates of each sample were tested for each cell.

Statistical analysis of ITS values reveals that the hypothesis that "additive has equal means" can be rejected with a probability of 95%. This means that the treatment type plays a very important role in the ITS values of treated mixes. The results of statistical analysis for Indirect Tensile Strength are shown in Table 4.7 for marl, sabkha, and dune sand mixes with EA and ESA.

Table 4.7: Result of Indirect Tensile Strength ANOVA at 5% significance level.

	Factors/Additives	Calculated F_{value}	P-value	Comment
Marl	Type of additives EA or ESA	14.01	0.013	Significant
Sabkha	Type of additives EA or ESA	38.57	0.003	Significant
Dune sand	Type of additives EA or ESA	52.19	0.002	Significant

4.4 Static Triaxial Test

Shear strength of marl, sabkha, and dune sand were studied after treatment by EA and ESA. The relationship between shear strength and normal stress for marl, sabkha and dune sand with EA and ESA is presented in Figure 4.10, 4.11, and 4.12, respectively. Analysis of these figures reveals that marl produced a higher shear strength ($\varphi = 27^o$ and C=292.5 kPa with EA, and $\varphi = 33^o$ and C=134 kPa with ESA) relative to the other treated soils and the shear strength of sabkha ($\varphi = 33^o$ and C=14.8 kPa with EA, and $\varphi = 31^o$ and C=14.4 kPa with ESA) which was higher than that of the dune sand ($\varphi = 30^o$ and C=25 kPa with EA, and $\varphi = 30^o$ and C=11.3 kPa with ESA).

The shear strength and related parameters for local soils treated with EA and ESA mixes are shown in Table 4.8. The results indicate that in general the maximum shear strength for mixes made with EA is higher than mixes made with ESA. The addition of ESA to the soil improves the angle of internal friction significantly compared to EA. While, the addition of ESA to the marl reduces values of cohesion significantly as compared to EA.

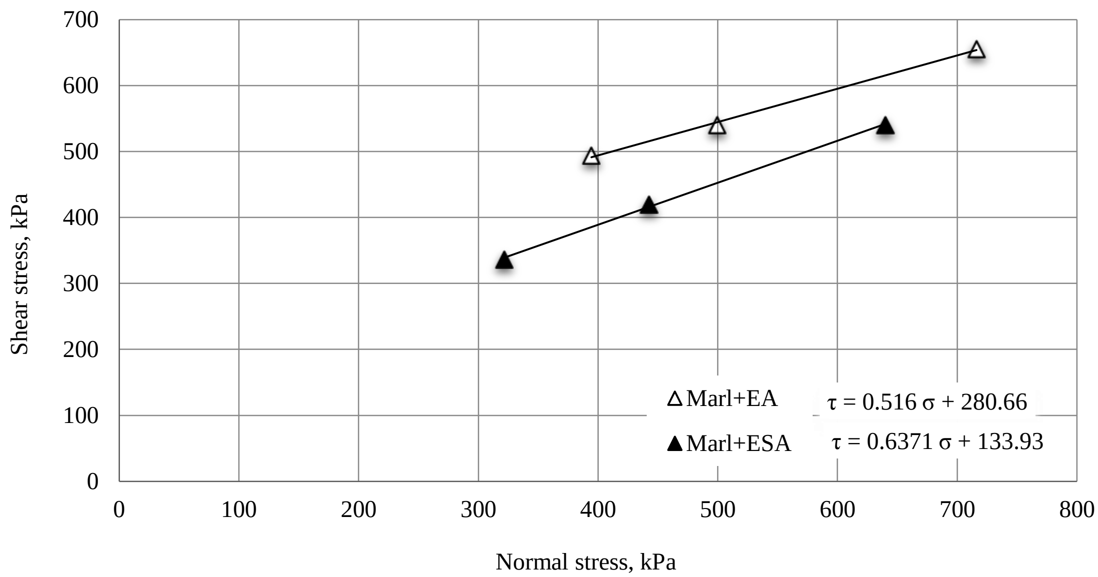


Figure 4.10: Mohr-Coulomb failure envelope for EA and ESA marl mixes.

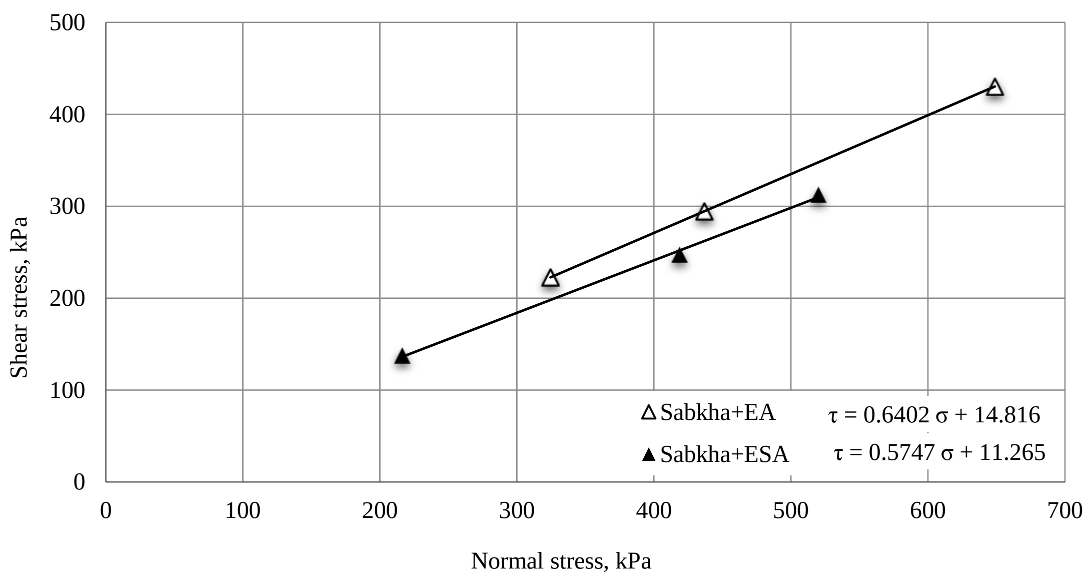


Figure 4.11: Mohr-Coulomb failure envelope for EA and ESA sabkha mixes.

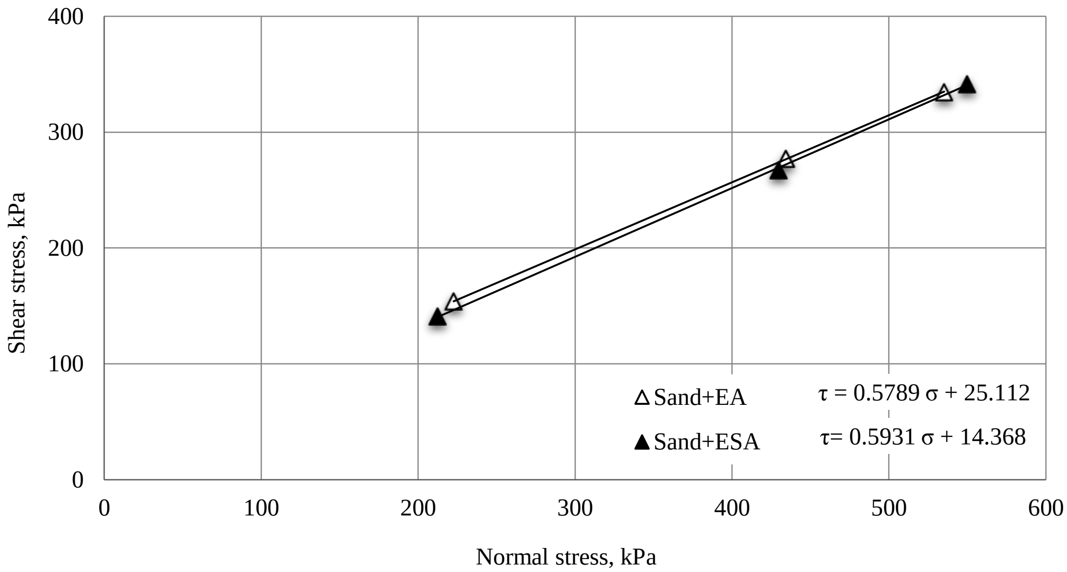


Figure 4.12: Mohr-Coulomb failure envelope for EA and ESA dune sand mixes

Table 4.8: Shear parameter for Mohr-Coulomb failure envelope of treated soils.

Treatment type	Soil Type	Angle of Internal Friction	Cohesion (kPa)
Emulsified Asphalt	Marl	27	292.5
	Sabkha	33	14.8
	Dune sand	30	25
Emulsified Sulfur Asphalt	Marl	33	134
	Sabkha	30	15
	Dune sand	31	11.4

The regression analysis for marl, sabkha and dune sand shows that there is a relationship between shear stress (τ) and normal stress, type of soil and type of additives. The best fit was plotted and developed in appendix A, as shown below:

$$\tau = 306 + 0.624\,\sigma - 41.1\,A - 89.5\,S \qquad (R^2 = 90\%) \qquad (4.1)$$

Where:

τ = shear stress, (kPa),

S= Type of soil (Marl=1, Sabkha=2 and Dune sand=3),

A= Type of additive (EA=1, ESA=2), and

σ = normal stress, (kPa)

4.5 Resilient Modulus (M_R) Test

Three specimens were tested for each material and each additive at 22°C and 40°C. The results were fitted to a relation between the deviator stress and resilient modulus.

The effect of various stress conditions on the resilient modulus was observed by varying the deviator and confining stresses applied on the soil samples as per AASTHO T-307 [54]. The general variation of the resilient modulus with different stress conditions for all soils with EA and ESA at 22^{o}C and 40^{o}C temperatures are presented in Figures 4.13 to 4.15. From the slope of the regression, it can be inferred that the resilient modulus at 22^{o}C and 40^{o}C is increased considerably with increasing deviator stress with good regression correlation.

The results show that the addition of EA to marl and dune sand reduces the M_R significantly as compared to ESA. The reduction for marl was about 20% and 15% for sabkha depending on the applied deviator stress.

Increasing the temperature to 40^{o}C causes lowering the modulus of resilience because stabilized mixes reduce stiffness due to softening of blinder with an increase in the deformation and hence a decrease in the M_R value. Summary of resilient modulus at 22^{o}C and 40^{o}C temperatures is shown in Tables 4.9 and 4.10, respectively.

Marl produced a higher M_R relative to the other soil whereas the M_R of sabkha was higher than that of dune sand as shown in Figures 4.13 to 4.15.

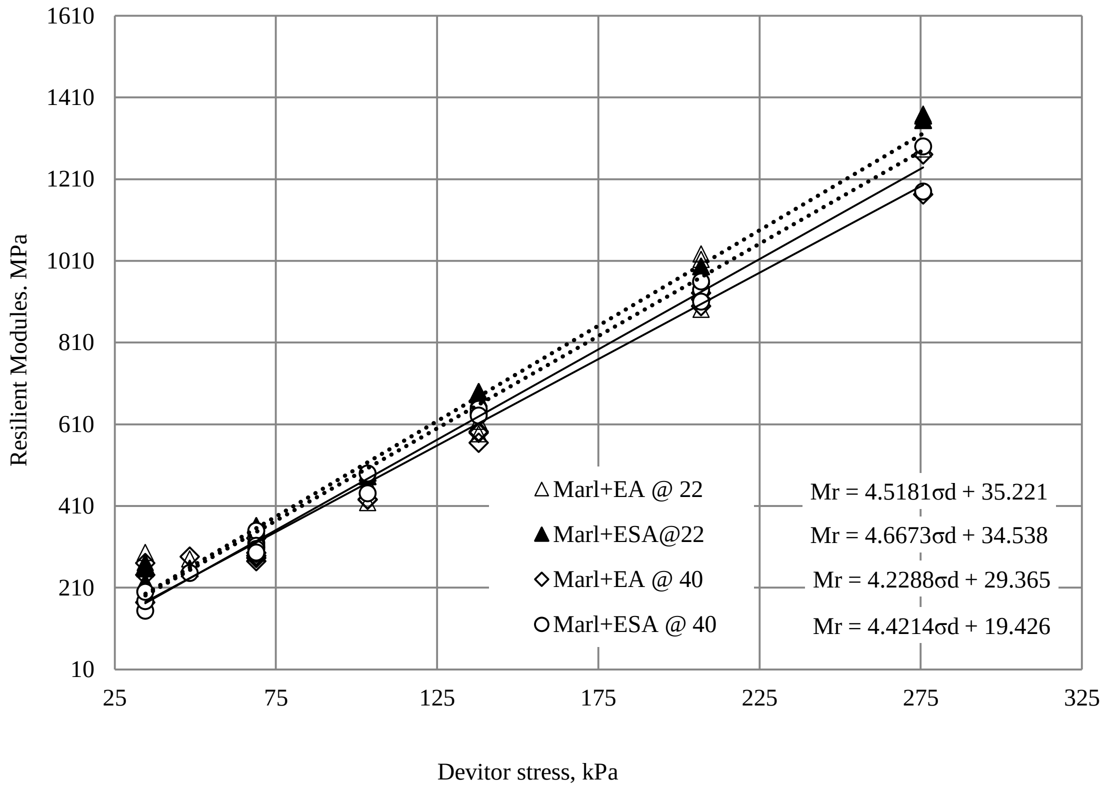


Figure 4.13: Variation of M_R with deviator stress for Marl with EA and ESA at 22ºC and 40ºC.

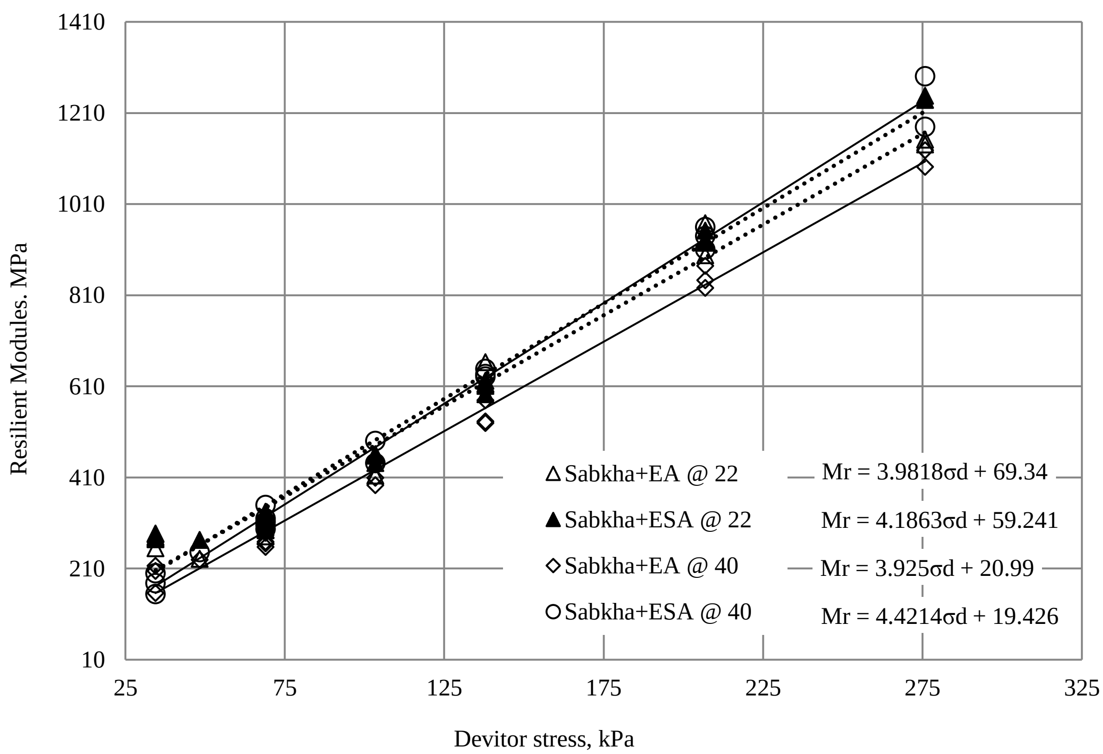


Figure 4.14: Variation of M_R with deviator stress for sabkha with EA and ESA at 22ºC and 40ºC.

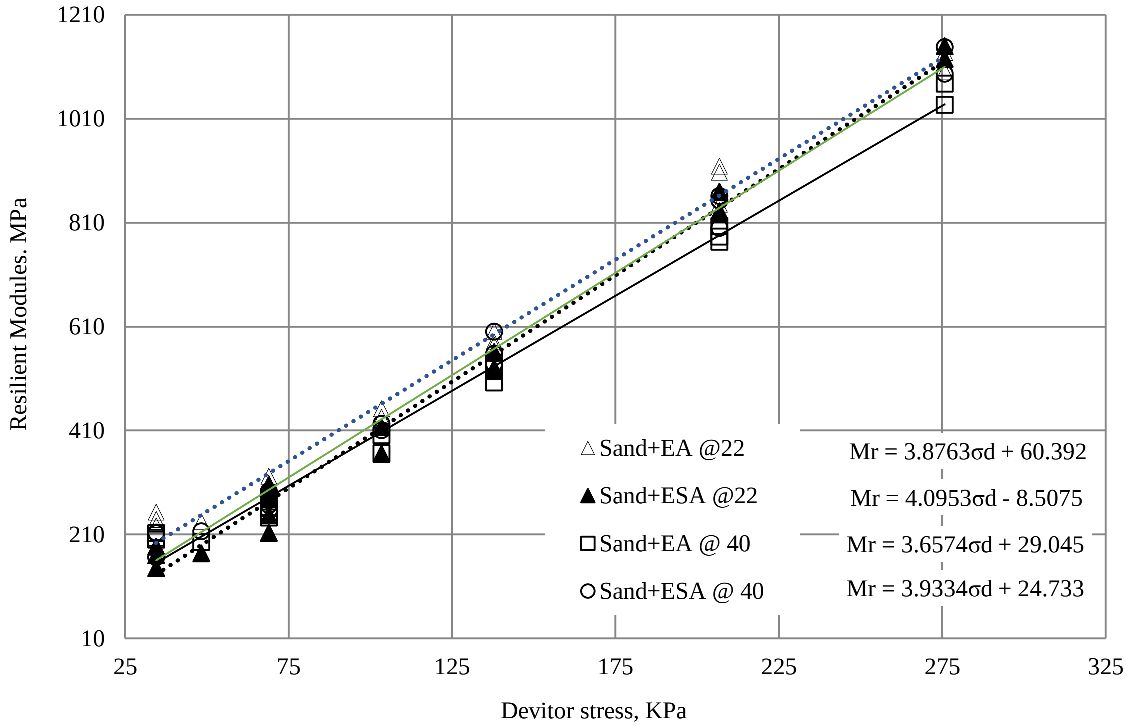


Figure 4.15: Variation of M_R with deviator stress for dune sand with EA and ESA at 22ºC and 40ºC.

Table 4.9: Resilient modulus (MPa) at 22ºC

Type of additive		EA			ESA		
Confining stress (kPa)	Deviator stress (kPa)	Sand	Marl	Sabkha	Sand	Marl	Sabkha
20.68	34.47	226	272	255	170	257	274
	48.26	235	281	232	174	257	273
	68.94	280	307	281	213	295	295
34.47	34.47	239	296	277	186	266	286
	68.94	309	301	310	247	362	335
	103.42	452	419	457	365	483	461
68.95	34.47	253	264	287	146	224	280
	68.94	302	323	334	304	358	318
	137.90	580	587	616	561	674	611
	206.84	846	1028	968	827	975	952
103.4	68.94	300	307	314	295	330	324
	137.9	575	617	663	530	689	622
	206.84	919	1014	925	870	973	925
	275.79	1101	1369	1141	1150	1355	1239
137.9	68.94	322	336	294	278	328	301
	103.42	436	465	414	417	492	442
	137.9	601	648	614	524	660	593
	206.84	907	892	898	832	997	931

Table 4.10: Resilient modulus (MPa) at 40ºC

Type of additive		EA			ESA		
Confining stress (kPa)	Deviator stress (kPa)	Sand	Marl	Sabkha	Sand	Marl	Sabkha
20.68	34.47	200	242	216	212	154	186
	48.26	196	286	229	216	246	230
	68.94	243	283	289	256	320	272
34.47	34.47	204	271	205	214	178	200
	68.94	262	289	269	267	350	296
	103.42	401	427	410	423	490	458
68.95	34.47	212	174	156	166	200	223
	68.94	278	332	290	284	313	289
	137.90	540	589	579	600	637	638
	206.84	783	932	826	853	940	880
103.4	68.94	253	275	257	276	305	293
	137.9	503	565	533	558	648	614
	206.84	804	916	843	862	911	890
	275.79	1037	1271	1092	1148	1291	1198
137.9	68.94	262	296	265	293	296	283
	103.42	367	426	393	411	441	409
	137.9	529	593	529	538	631	576
	206.84	773	900	875	800	960	830

Table 4.11 presents the results of ANOVA analysis for resilient modulus (M_R). Analysis of M_R data using General Linear Model (4-Way analysis ANOVA) technique shows that confining stress and deviator stress have a significant effect on M_R for marl, sabkha, and dune sand mixes whereas the additive type has an insignificant effect on M_R for the three types of soil. While the temperature has a significant effect on M_R for the three types of soil. This means that the confining stress and deviator stress for marl, sabkha, and dune sand mixes and temperature have a significant effect on M_R values. While, on the other hand, the additive type has an insignificant effect for marl, sabkha and dune sand. This means that the additive type effect can be neglected when calculating the resilient modulus.

Table 4.11: Results of Resilient Modulus ANOVA at 5% significance level.

	Factors/Additives	Calculated F_{value}	P-value	Comment
Marl	Type of additives EA or ESA	0.54	0.467	Insignificant
	Confining stress	36.30	0.000	Significant
	Deviator stress	167.04	0.000	Significant
	Temperature	4.18	0.045	Significant
Sabkha	Type of additives EA or ESA	1.27	0.264	Insignificant
	Confining stress	38.94	0.000	Significant
	Deviator stress	179.51	0.000	Significant
	Temperature	7.18	0.009	Significant
Dune sand	Type of additives EA or ESA	0.14	0.713	Insignificant
	Confining stress	38.65	0.000	Significant
	Deviator stress	157.88	0.000	Significant
	Temperature	3.43	0.023	Significant

The regression analysis for marl, sabkha and dune sand shows that there is a relationship between resilient modulus (M_R) and Temperature, deviator stress, confining pressure and type of additives. The best fit was plotted and developed in appendix A, as shown below:

$$M_R = 166.6 - 2.1\,T - 35.8\,S + 9.7\,A - 0.25\,\sigma_c + 4.2\,\sigma_d \qquad (R^2=98\%) \qquad (4.2)$$

Where:

M_R = Resilient modulus, (MPa),

T = Temperature, (^{o}C),

S= Type of soil (Marl=1, Sabkha=2 and Dune sand=3),

A= Type of additive (EA=1, ESA=2),

σ_c = Confining Pressure, (kPa), and

σ_d = Deviator stress, (kPa)

4.6 Dynamic Triaxial Test

Dynamic Triaxial test was proficient on the treated marl, sabkha, and dune sand specimens to evaluate the permanent deformations under dynamic loading condition. The effects of various deviator stress (137.8 to 551.5 kPa) and stabilizer type (EA and ESA) at 22^{o}C and 40^{o}C temperature on the permanent deformations were studied for all soils and additive combinations. Three samples of each material combinations were tested at each temperature, the total number of tested samples were 138.

Test results were plotted for vertical permanent strain as ordinate and number of load repetitions as horizontal coordinate. The corresponding deformation curves for the tested mixtures are given in Figures 4.16 to 4.27. It can be seen from these figures that the deformation curve versus loading time can be divided into three distinct regions: primary stage (range A), where the samples compact an initial amount during the very first load cycles and the strain rate decreases, secondary stage (range B) where they usually continue to compact gradually over many load cycles and the strain rate is constant, and the tertiary stage (range C) where the strain rate increases exponentially.

The deformation curve in the secondary stage region is plotted as a straight line on a log–log scale so it is also referred to as steady state linear deformation. In this phase the material is considered to be in "range B" behavior. This linear deformation continues indefinitely and the material does not reach failure. However, when a higher stress or with a greater number of load cycles are applied, the permanent deformation is more elevated and the material might enter into ''range C" behavior and, finally, reaches failure. Lastly, if the applied stress is even higher, the permanent strain accumulates rapidly in a low number of load cycles. In this condition the material will reach failure and rutting will take place very quickly. In this phase the material is in “range C” behavior.

The stress levels in this test were selected on the basis of the stresses supported by a well-designed, constructed section of pavement of low traffic to high traffic roads [34]. Therefore, according to the shakedown concept [55], if the section is well-designed, it’s pavement structural behavior should be in stable conditions, i.e., it should be within at the most, in ‘‘range B”.

For soil with EA, Figures 4.16 and 4.17 show that marl at 22^{o}C and 40^{o}C, with all stress levels, deformation increase continue indefinitely and the material does not reach failure so the material exhibits “range B” behavior.

Figures 4.18 and 4.19 show that as regards stress levels 551.5, 482.6, and 413.6 kPa, sabkha with EA at 22^{o}C and 40^{o}C behaved as in ‘‘range B”. However, when N increased, it has given rise to an increment in permanent deformation and the material might pass over to ‘‘range C”. While at stress levels 275.8, and 137.8 kPa, sabkha with EA at 22^{o}C behaved as in “range B” and did not pass over to “range C”.

Figure 4.20 shows that, at stress levels 137.8, 275.8, and 413.6 kPa, dune sand with EA at 22^{o}C behaved as in “range B”. However, when N increases, it gives rise to an increment in permanent deformation and the material might pass over to “range C” while at stress levels of 482.6, and 551.5 kPa, sabkha with EA at 22^{o}C behaves as in “range C” because the applied stress was even higher, the permanent strain accumulates rapidly in a low number of load cycles. In this condition, the material reached failure, and rutting took place very quickly. Also, in Figure 4.21, dune sand with EA at 40^{o}C and stress levels of 413.6, 482.6, and 551.5 kPa, exhibited a trend in much of the same way as by dune sand at 22^{o}C and stress levels of 482.6, and 551.5 kPa, but it reached a failure stage at lower number of repetitions.

As a conclusion from dynamic triaxial results for soil with EA, when the applied axial stress increased, the magnitude of the axial permanent strain accumulation increased. The increase in strain was very significant at higher stress levels and higher temperatures, whereas low strains were accumulated at lower stress levels and lower temperatures. This implies that the asphalt mix would experience considerable amount of permanent deformation under high wheel loads from vehicles at high temperatures in the field, hence significant rutting is expected under such conditions.

For blends with ESA, Figure 4.22 shows that marl with ESA at 22°C and stress of 551.5 kPa behaved as in "range B". When N increases, it has given rise to an increment in permanent deformation. It is possible that if a higher N were applied, the material might pass over to "range C". While at stress levels of 482.6, 275.8, and 137.8 kPa, it behaved as in "range B". Figure 4.23 shows that at stress levels of 551.5, 482.6, and 413.6 kPa, marl with ESA at 40°C behaved as in "range B". This behavior continued indefinitely and the material did not reach a failure stage.

Figures 4.24 and 4.25 show that, at stress levels of 551.5, 482.6, and 413.6 kPa, sabkha with ESA at 22°C behaved as in "range B", but with a greater number of load cycles the material might enter into "range C" behavior and finally, reach failure. At stress levels of 551.5, 482.6, and 413.6 kPa, sabkha with ESA at 40°C behaved as in "range B" and it was continued indefinitely where the material did not reach failure.

Figure 4.26 shows, at stress levels of 413.6, 482.6 and 551.5 kPa, dune sand with ESA at 22°C behaved as in ''range C" because the applied stress was high and the permanent strain accumulated rapidly in a low number of load cycles. In this condition the material reached failure. While, at stress of 275.8 kPa, it behaved as in ''range B". Also, in Figure 4.27, dune sand with ESA at 40^{o}C and stress levels of 482.6, and 551.5 kPa exhibited a trend in much the same way as dune sand at 22^{o}C and stress levels of 482.6, and 551.5 kPa, but reaches a failure stage at high number of repetitions.

As a conclusion from dynamic triaxial results for soil with ESA, the magnitude of the axial permanent strain accumulation increased when the applied axial stress increased. The increase in strain was very significant at high stress levels, whereas low strains were accumulated at low stress levels. This implies that the asphalt mix would experience considerable amount of permanent deformation under high wheel loads from vehicles in the field; hence, significant rutting is expected under such condition.

When comparing the permanent deformation between soil with EA and soil with ESA, three elements were considered: loads or stress, temperature and type of additive.

Firstly, EA blends and ESA blends have the same rutting behavior when increasing or decreasing the stress levels. However, it appears from the results of a rutting experiment that ESA blends are more affected with change in the stress levels as compared to EA blends.

Secondly, permanent deformation for ESA mixes was higher than that for EA mixes with increasing temperature levels.

Finally, Treatment of sabkha and dune sand with ESA increased the permanent axial strains and significantly decreased the number of repetitions as compared to EA addition. Marl exhibits a trend in much of the same way as did sabkha and dune sand, but it did not reach to tertiary stage.

From Dynamic Triaxial test, rutting parameters intercept “a”, and slop “b” is obtained from the regression analysis of the linear portion (second stage) of the permanent deformation curve.

The model for the linear portion (second stage) of the permanent deformation curve is a log-log relationship between the permanent strain and number of load repetitions.

$$\varepsilon_p = aN^b \tag{4.3}$$

Where:

ε_p: Accumulated Permanent Strain at N cycle,

N: Number of Load Repetitions, and

a,b: Regression Coefficients.

The regression analysis for regression coefficients (“a” and “b”) for marl, sabkha and dune sand shows that there is a relationship between regression coefficients and Temperature, deviator stress and type of additives. The best models for each treated soil was plotted and developed in appendix A, as shown below:

For marl

$$\varepsilon_p = (-8156 + 6376A + 1.77\sigma_d + 82.3T)\, N^{(0.12+0.003A+0.0006\sigma_d-0.002T)} \tag{4.4}$$

(R^2=75%)

For sabkha

$$\varepsilon_p = (-5170 + 2605A - 6.64\sigma_d + 319T)\, N^{(0.43+0.154A+0.0007\sigma_d-0.007T)} \tag{4.5}$$

(R^2=60%)

For dune sand

$$\varepsilon_p = (-838 + 1847A - 2.33\sigma_d + 32T)\, N^{(0.05-0.3A+0.001\sigma_d-0.008T)} \tag{4.6}$$

(R^2=65%)

Where:

ε_p: Accumulated Permanent Strain at N cycle,

N: Number of Load Repetitions, and

T = Temperature, (^{o}C),

A= Type of additive (EA=1, ESA=2),

σ_d = Deviator stress, (kPa), and

Confining stress (σ_c) = 68.8 kPa

From previous equations, for marl with EA and with ESA, intercept increased with the increase in temperature and deviator stress while slope decreased with the increase in temperature and it increased with the increase in deviator stress. For sabkha and dune sand with EA and ESA, intercept increased with the increase in temperature and slope decreased with the increase in the temperature too. Also, intercept decreased with the increase in deviator stress and slope increased with the increase in the deviator stress too.

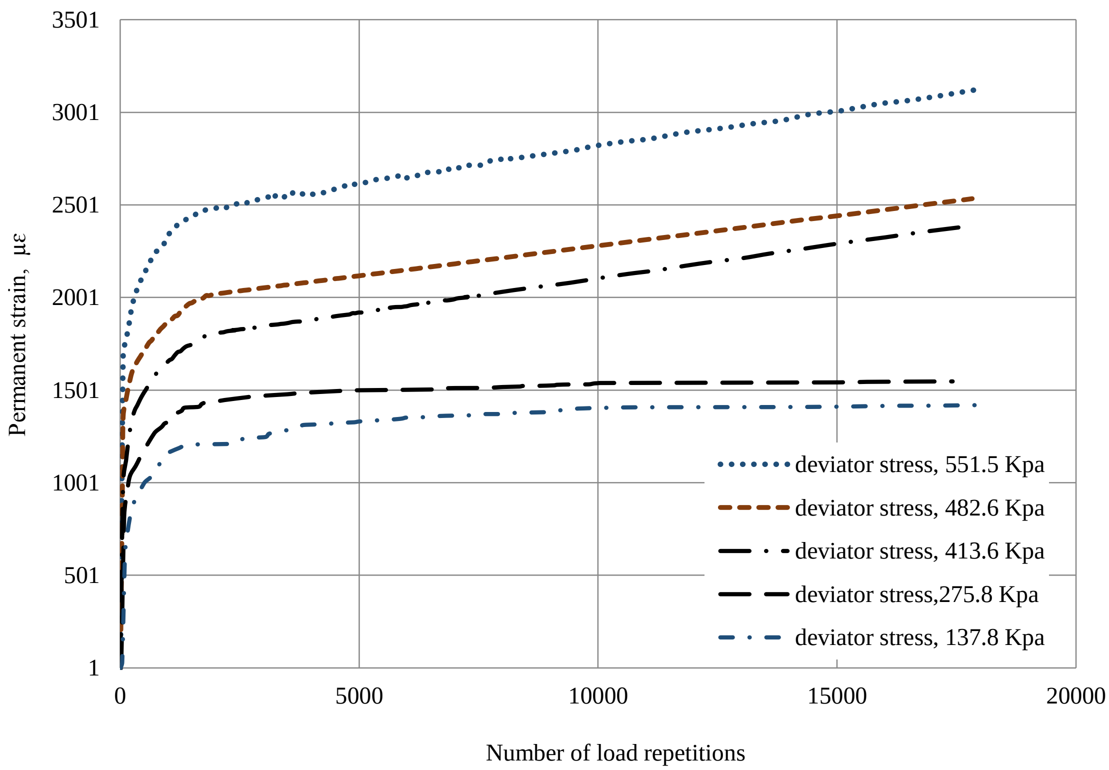


Figure 4.16: Relationship between permanent axial strains and load cycles for Marl with EA at 22ºC

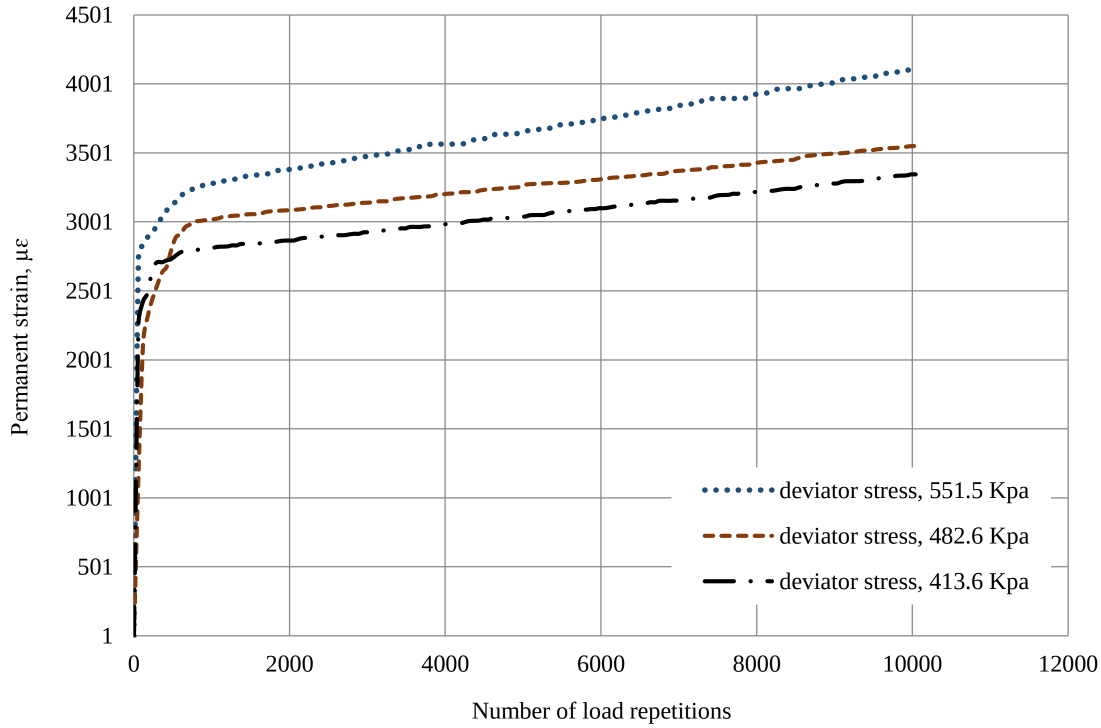


Figure 4.17: Relationship between permanent axial strains and load cycles for Marl with EA at40ºC

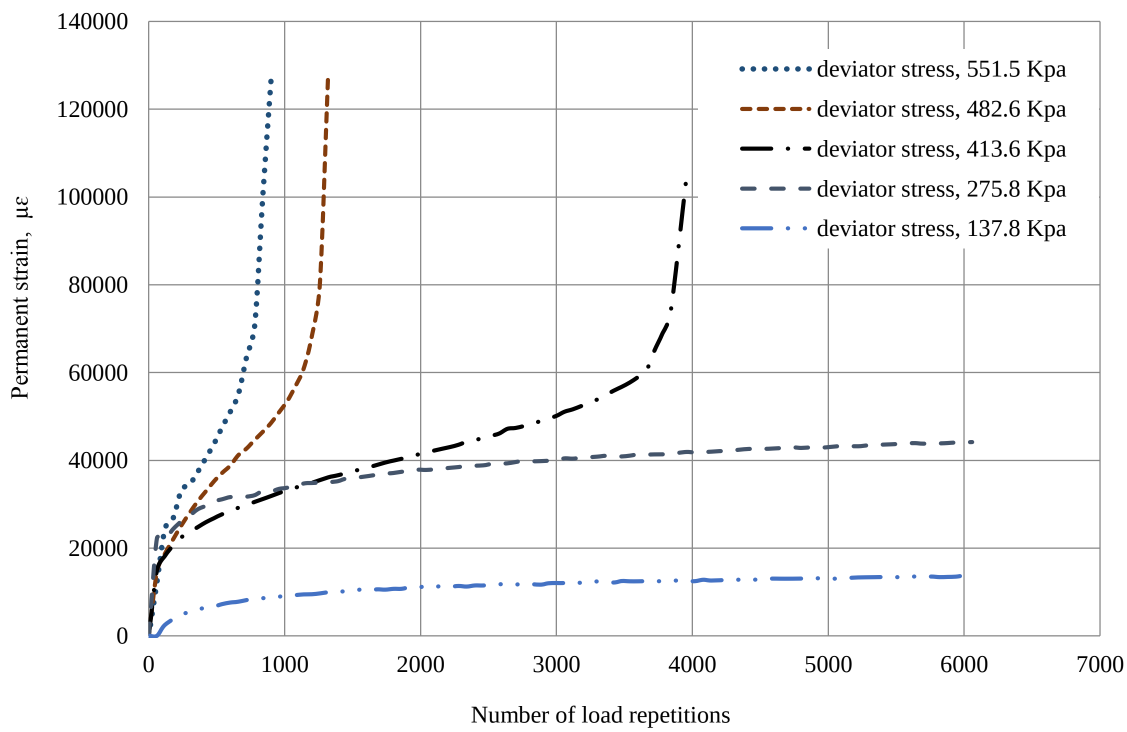


Figure 4.18: Relationship between permanent axial strains and load cycles for sabkha with EA at 22ºC

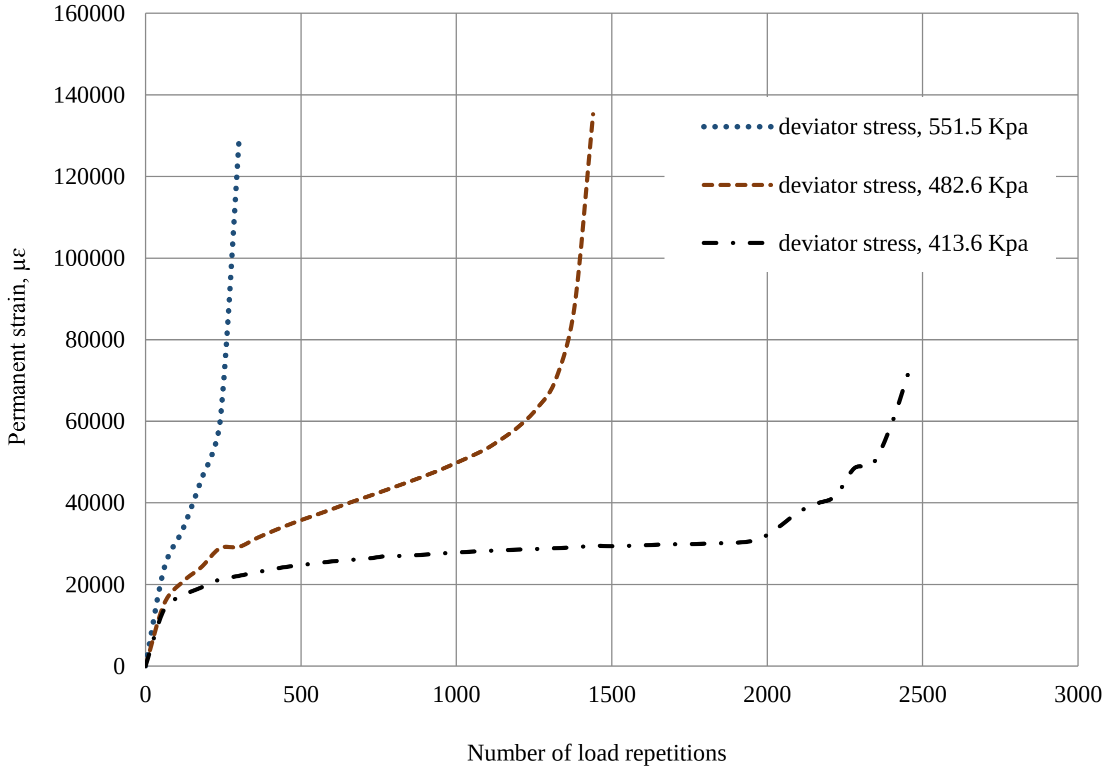


Figure 4.19: Relationship between permanent axial strains and load cycles for sabkha with EA at 40°C

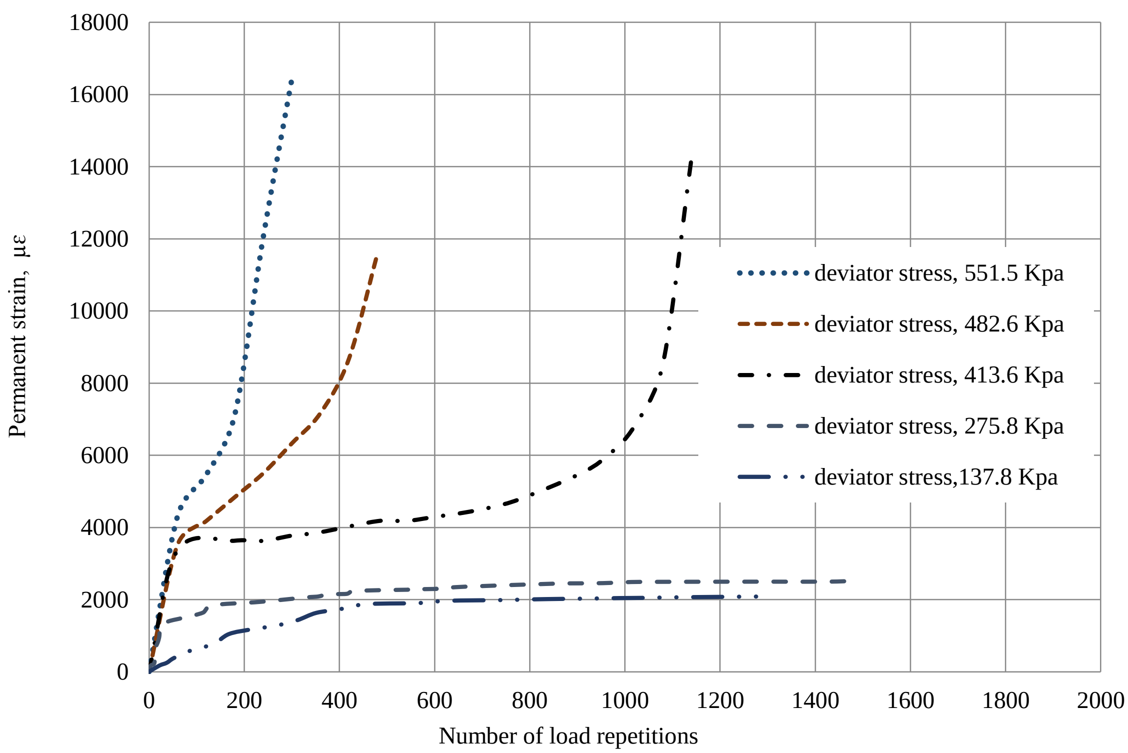


Figure 4.20: Relationship between permanent axial strains and load cycles for dune sand with EA at 22°C

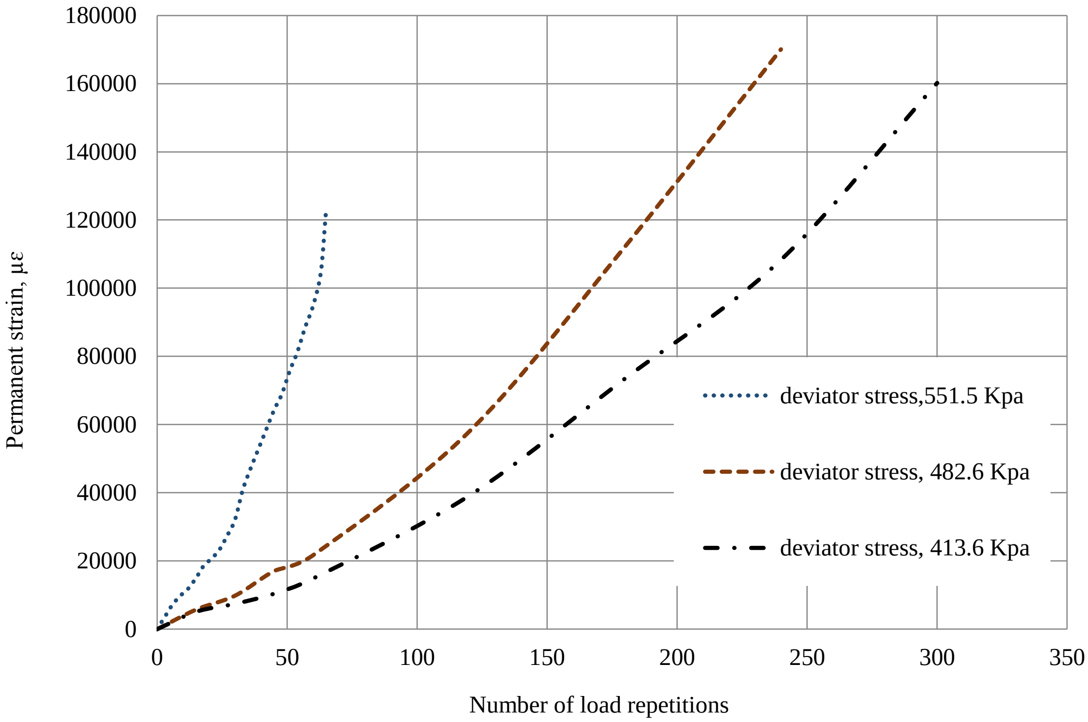


Figure 4.21: Relationship between permanent axial strains and load cycles for dune sand with EA at 40ºC.

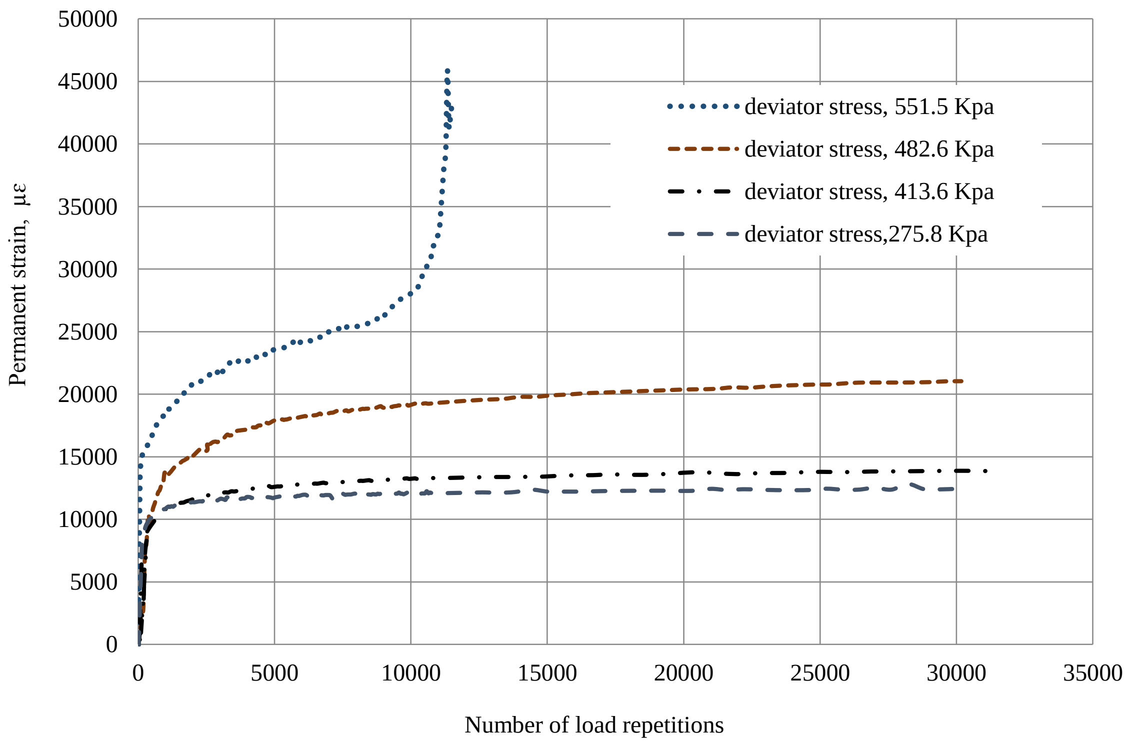


Figure 4.22: Relationship between permanent axial strains and load cycles for Marl with ESA at 22ºC

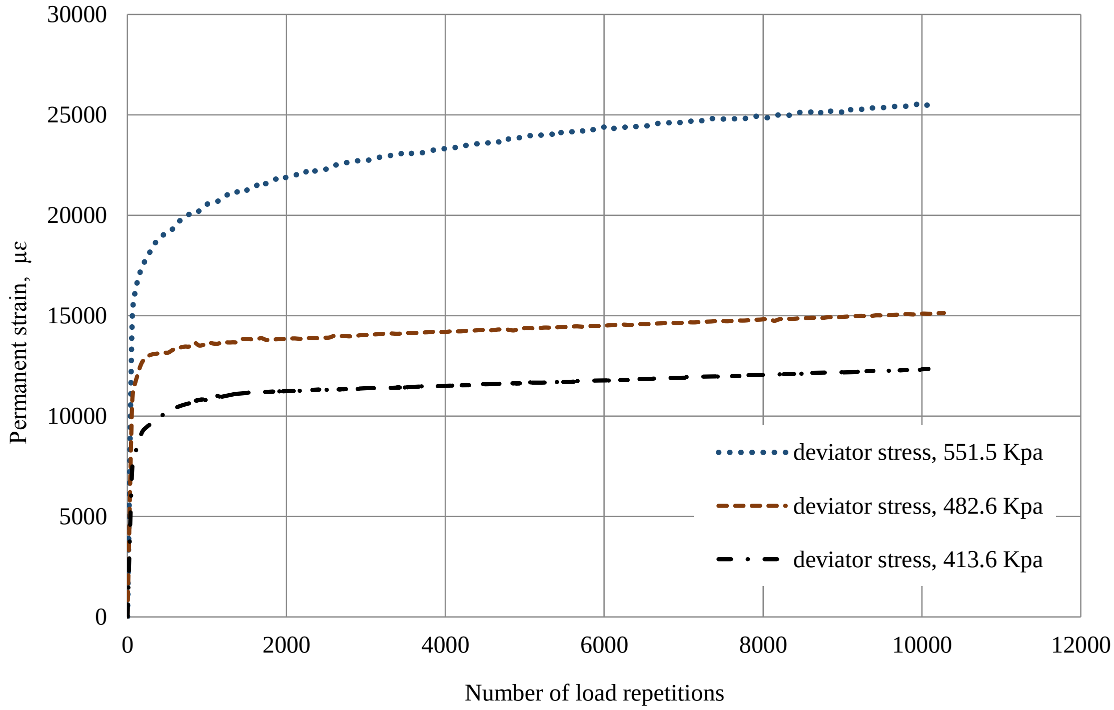


Figure 4.23: Relationship between permanent axial strains and load cycles for Marl with ESA at 40°C

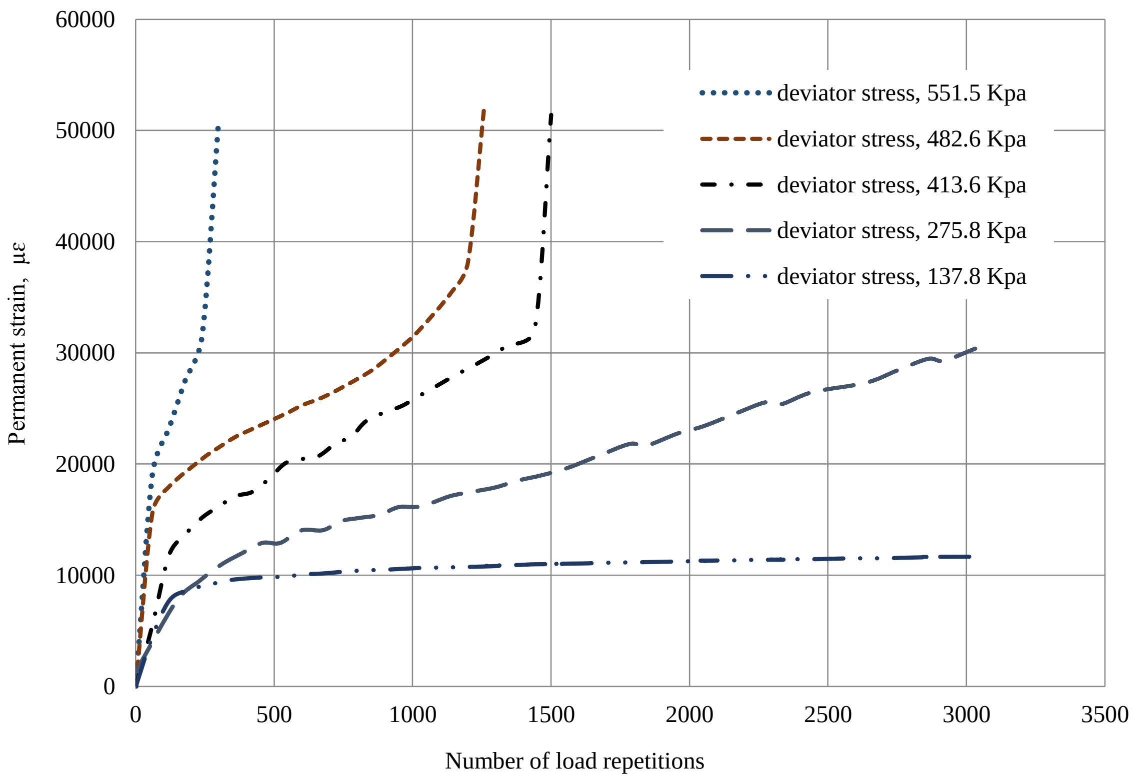


Figure 4.24: Relationship between permanent axial strains and load cycles for sabkha with ESA at 22°C

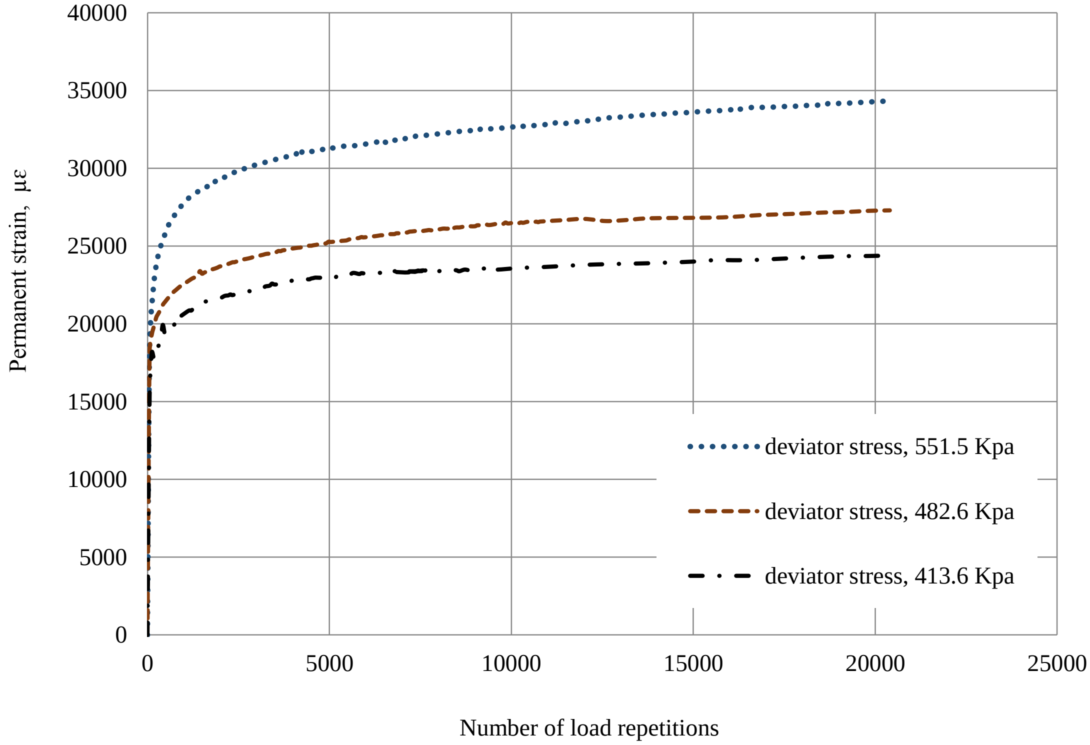


Figure 4.25: Relationship between permanent axial strains and load cycles for sabkha with ESA at 40ºC.

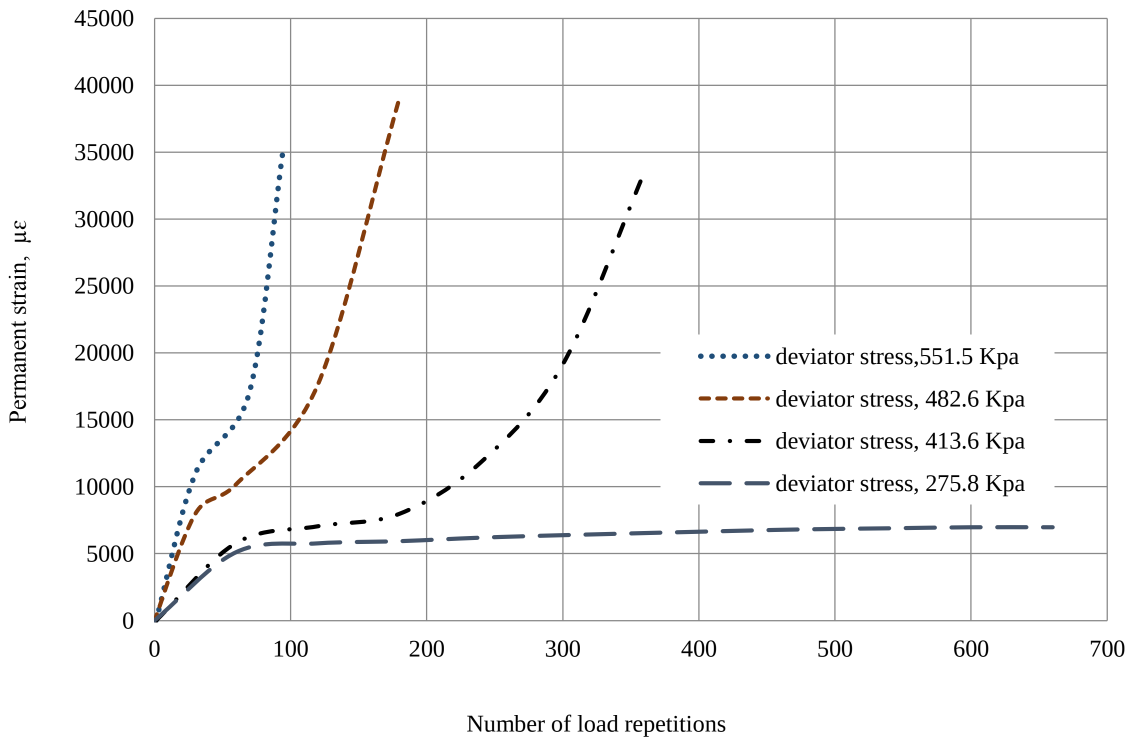


Figure 4.26: Relationship between permanent axial strains and load cycles for dune sand with ESA at 22ºC

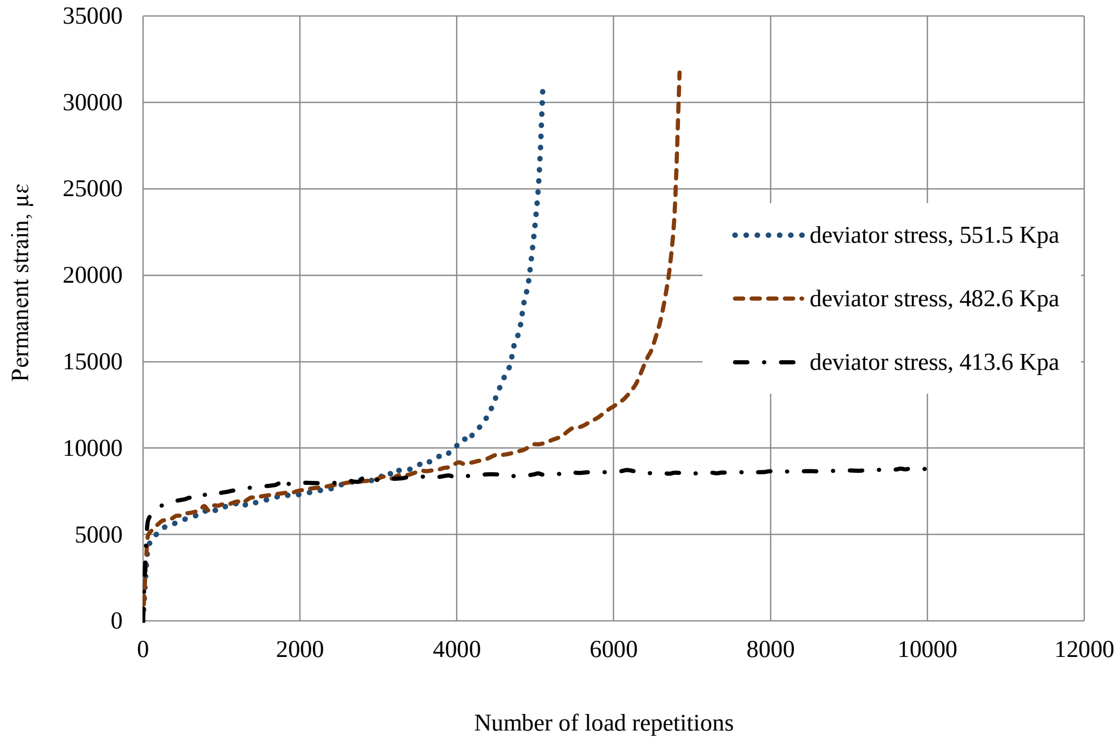


Figure 4.27: Relationship between permanent axial strains and load cycles for dune sand with ES at 40°C

4.6.1 Dynamic Triaxial Results For Subgrade Soil

Marl and sabkha were mixed with the optimum water content. Samples were fabricated to specimens of 200mm diameter by 400mm height. Each specimen was compacted to the corresponding density obtained in the proctor compaction test. For dune sand, specimens were prepared by vibratory compaction methods using a vibration table. Three samples for each soil were prepared and cured at 22°C for 72 hours and tested under a repeated load for confining stress of 69 kPa and deviator stress of 138 kPa at 22°C. The typical responses for sabkha and marl are shown in Figure 4.28, and Figure 4.29 shows the typical responses for dune sand. Results indicate that marl produced a higher resistance to deformation as compared to the other soil and the resistance to deformation of the sabkha was found to be higher than that of the dune sand.

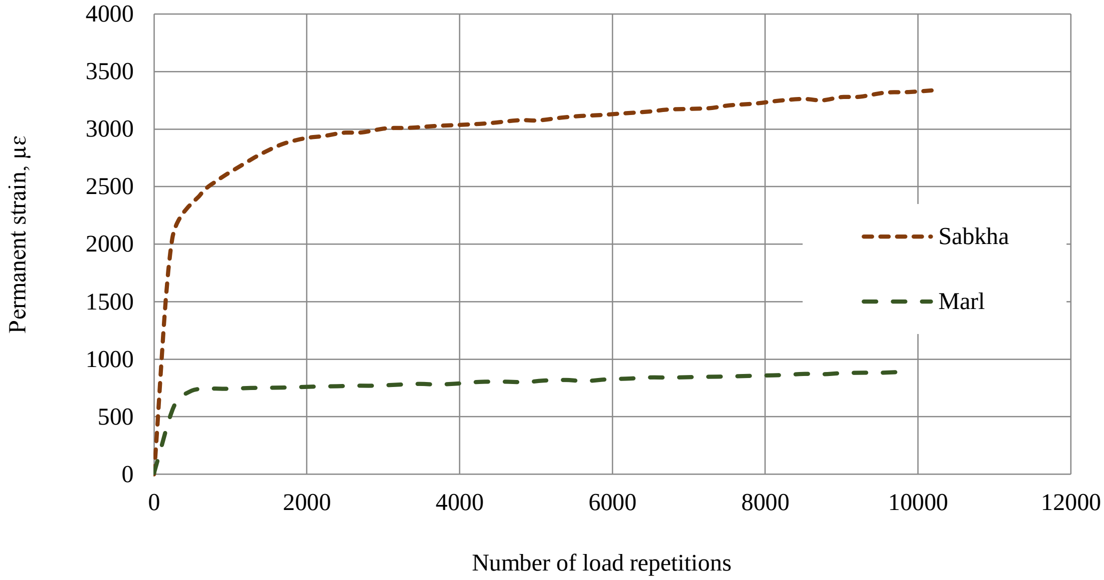


Figure 4.28: Relationship between permanent axial strains and load cycles for sabkha and Marl subgrade.

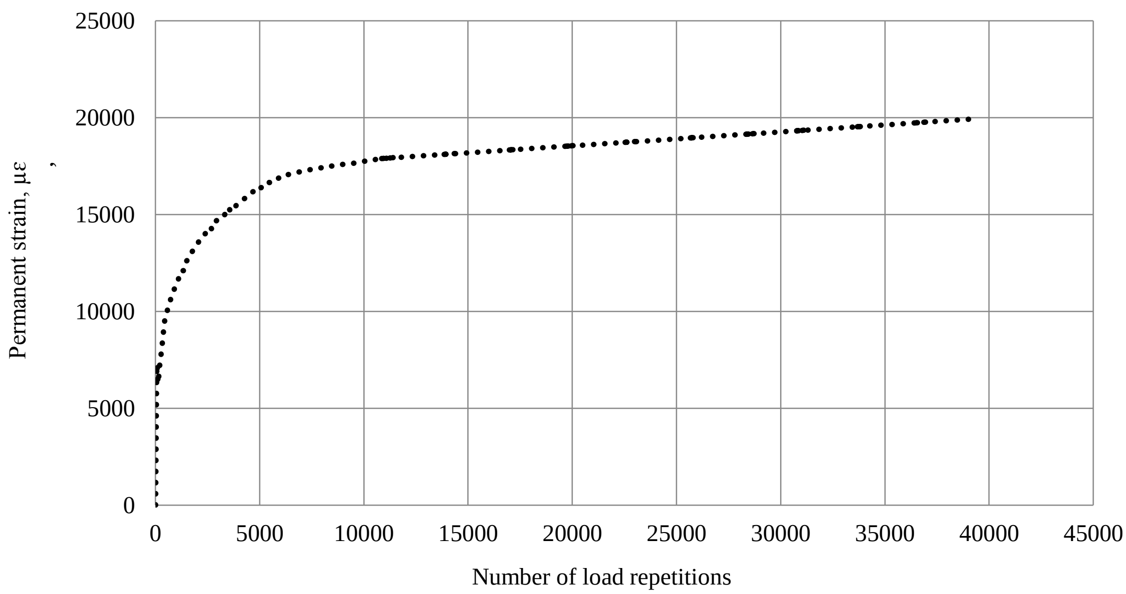


Figure 4.29: Relationship between permanent axial strains and load cycles for dune sand subgrade

4.6.2 Determination of Permanent Deformation Parameters

The estimation of the rutting parameters, intercept "a" and slop "b" were obtained as discussed in section 4.6. These two parameters were then used to determine the permanent deformation parameters, α (ALPHA) and μ (GNU), using Equ. 2.8. These two parameters were then used in the VESYS modeling program to determine the amount of rutting of pavement structure. Summary of the calculated values for these parameters is given in Table 4.12 which shows that the values for Alpha decreased with an increase in deviator stress because of increase in permanent deformation slop but, the values for μ increase with increase in the deviator stress.

Table 4.12: Summary of Rutting Parameters α and μ for base, subbase and subgrade.

Soil	Additive	Deviator stress, kPa	a(με)		b		μ		α	
			22°C	40°C	22°C	40°C	22°C	40°C	22°C	40°C
Marl	EA	137.8	491.83	--	0.12	--	0.22	--	0.88	--
		275.8	718.72	--	0.09	--	0.15	--	0.91	--
		413.69	740.42	2098.9	0.11	0.04	0.16	0.16	0.88	0.96
		482.63	958.24	2165.1	0.10	0.05	0.16	0.17	0.91	0.95
		551.58	1204.8	2161.9	0.09	0.06	0.19	0.20	0.91	0.94
	ESA	275.8	7655.2	--	0.05	--	0.98	--	0.95	--
		413.69	7002.2	5790	0.07	0.09	0.97	1.02	0.93	0.91
		482.63	6782	10465	0.11	0.04	1.43	0.72	0.88	0.91
		551.58	6567.0	10639	0.15	0.09	1.74	1.72	0.85	0.91
Sabkha	EA	137.8	1098.7	--	0.3	--	1.22	--	0.70	--
		275.8	11355	--	0.02	--	0.42	--	0.98	--
		413.69	3692.9	7172.5	0.32	0.20	2.16	3.53	0.68	0.8
		482.63	1693.7	2494.8	0.49	0.43	1.41	2.29	0.51	0.57
		551.58	1810.2	1570.5	0.52	0.65	1.49	1.96	0.48	0.35
	ESA	137.8	5430.6	--	0.1	--	1.97	--	0.90	--
		275.8	1431.4	--	0.35	--	1.19	--	0.64	--
		413.69	1635	11578	0.38	0.08	1.17	1.74	0.62	0.92
		482.63	1880.4	13711	0.25	0.07	0.79	1.65	0.75	0.93
		551.58	2813	13245	0.36	0.11	1.6	2.24	0.64	0.89
Dune sand	EA	137.8	1231.4	--	0.07	--	0.32	--	0.93	--
		275.8	1094.8	--	0.11	--	0.28	--	0.88	--
		413.69	1273.9	645.61	0.19	0.75	0.44	0.38	0.81	0.26
		482.63	625.81	389.94	0.40	0.98	0.41	0.27	0.60	0.02
		551.58	1078.2	1406.1	0.34	0.88	0.57	0.83	0.66	0.12
	ESA	275.8	3083.5	--	0.13	--	0.83	--	0.87	--
		413.69	1771.2	4595.9	0.29	0.07	0.90	0.54	0.71	0.93
		482.63	2428.6	3133.2	0.35	0.11	1.40	0.54	0.65	0.89
		551.58	1888.0	2379.1	0.52	0.14	1.53	0.51	0.48	0.86
Marl *		68.9	329.75		0.09		0.07		0.91	
Sabkha *		68.9	1576.40		0.08		0.20		0.85	
Dune sand *		68.9	7429.60		0.11		1.13		0.89	

*Subgrade layer materials were tested at one temperature 22°C

The results of statistical analysis for μ and α are shown in Table 4.13 and Table 4.14 for marl, sabkha, and dune sand mixes with EA and ESA. The "F–test" results in these tables show that the deviator stress has an insignificant effect on the μ and α at 95% significance level. Also, type of additives has an insignificant effect on α for all soil but, a significant effect on μ for marl and dune sand. Moreover, the temperature has a significant effect on α of marl and μ for both sabkha and dune sand while it remains insignificant on α for sabkha and dune sand, and μ for marl.

Table 4.13: Results of μ ANOVA at 5% significance level.

	Factors/Additives	Calculated F_{value}	P-value	Comment
Marl	Type of additives EA or ESA	57.53	0.000	Significant
	Deviator Stress	1.56	0.274	Insignificant
	Temperature	0.54	0.485	Insignificant
Sabkha	Type of additives EA or ESA	0.87	0.374	Insignificant
	Deviator Stress	1.17	0.387	Insignificant
	Temperature	5.89	0.038	Significant
Dune sand	Type of additives EA or ESA	7.95	0.023	Significant
	Deviator Stress	1.15	0.398	Insignificant
	Temperature	4.68	0.043	Significant

Table 4.14: Results of α ANOVA at 5% significance level.

	Factors/Additives	Calculated F_{value}	P-value	Comment
Marl	Type of additives EA or ESA	1.40	0.271	Insignificant
	Deviator Stress	1.17	0.393	Insignificant
	Temperature	5.48	0.047	Significant
Sabkha	Type of additives EA or ESA	3.25	0.105	Insignificant
	Deviator Stress	1.25	0.355	Insignificant
	Temperature	1.77	0.216	Insignificant
Dune sand	Type of additives EA or ESA	3.92	0.083	Insignificant
	Deviator Stress	0.80	0.558	Insignificant
	Temperature	0.76	0.410	Insignificant

The results of regression analysis show that there is a relationship between μ and type of additives, temperature and deviator stress. The relationship, the best fit was plotted and developed as shown below:

For marl $\mu = -1.0 + 1.0\ A - 0.007\ T + 0.0009\ \sigma d$ (R2=84%) (4.7)

For sabkha $\mu = 0.7 - 0.26\ A + 0.05\ T - 0.00017\ \sigma_d$ (R^2=48%) (4.8)

For dune sand $\mu = 0.03 + 0.42\ A - 0.02\ T + 0.0013\ \sigma_d$ (R^2=65%) (4.9)

For all soils $\mu = -0.04 + 0.4\ A - 0.008\ S + 0.007\ T + 0.0006\ \sigma_d$ (R^2=61%) (4.10)

Where:

T = Temperature, (°C),

S= Type of soil (Marl=1, Sabkha=2 and Dune sand=3),

A= Type of additive (EA=1, ESA=2),

σd = Deviator stress, (kPa), and

Confining stress (σ_c) = 68.8 kPa.

The results also show that there is a relationship between α and type of additives, temperature and deviator stress. The relationship, the best fit was plotted and developed as shown below:

For marl $\alpha = 0.8 - 0.01\ A + 0.002\ T + 0.00005\ \sigma_d$ (R^2=33%) (4.11)

For sabkha $\alpha = 0.5 + 0.15\ A + 0.007\ T - 0.0007\ \sigma_d$ (R^2=45%) (4.12)

For dune sand $\alpha = 0.9 + 0.28\ A - 0.007\ T - 0.001\ \sigma_d$ (R^2=51%) (4.13)

For all soils $\alpha = 1.06 + 0.14\ A - 0.134\ S + 0.0005\ T + 0.0006\ \sigma_d$ (R^2=41%) (4.14)

Where:

α = Alpha,

T = Temperature, (°C),

A= Type of additives (EA =1; ESA =2), and

S= Type of soil (Marl=1, Sabkha=2 and Dune sand=3), and

σ_d = Deviator stress, (kPa), and

Confining stress (σ_c) = 68.8 kPa.

4.7 Summary

Tests were conducted on local soils treated mixes with EA and ESA. Several trial mixes were made for different EA and ESA content ranges from 3% to 18% of dry soils weight. The designed mixtures were subjected to: Marshall Stability test, Tensile Strength test, Resilient Modules (M_R) test, and Static Triaxial test (shear strength). The behavior of dune sand, marl, and sabkha mixes under dynamic loads were studied by using Dynamic Triaxial test to generate useful laboratory data which can depict the performance of such mixes under traffic conditions. Tests were conducted at 22°C and 40°C at different stress levels.

CHAPTER 5

RUTTING ANALYSIS

5.1 Rutting Model

Data from the dynamic Triaxial test was used to establish a rutting model. Three stabilized soils: marl, sabkha and dune sand were treated with EA and ESA additives to be used as constriction base material. In order to predict the rutting response, first, pavement system and traffic characteristics were selected. After, the responses of the pavement in terms of stresses were computed using the 3D-MOVE Analysis computer program [56]. Then, pavement materials properties (i.e. Resultant Modulus) were computed from these test results. Finally, layer rutting was determined using TTI VESYS5W [57].

5.1.1 Pavement Systems (cases analyzed).

Two types of pavement structures were simulated using VESYS model. The first structure is a conventional flexible pavement, consisting of 5cm asphalt concrete as the surface layer, improved EA or ESA marl soils as the base, and marl soil subgrade. This structure consists of two cases (case 1 and case 2) based on the treatment type (EA and ESA) as shown in Figure 5.1.

The second structure is similar to the first structure, but the number of layers is four with an additional subbase layer. This system is used when subgrade is sabkha or dune sand. The use of subbase layer below the base in this system to serve as the foundation for the pavement structure, transferring traffic loads to the subgrade, and providing drainage layer. Since CBR of subgrade (dune sand and sabkha) is between 10% and 15%, 150mm subbase layer is used [58]. This structure consists of eight cases (case 3 to case 10) as shown in Figure 5.2 and Figure 5.3.

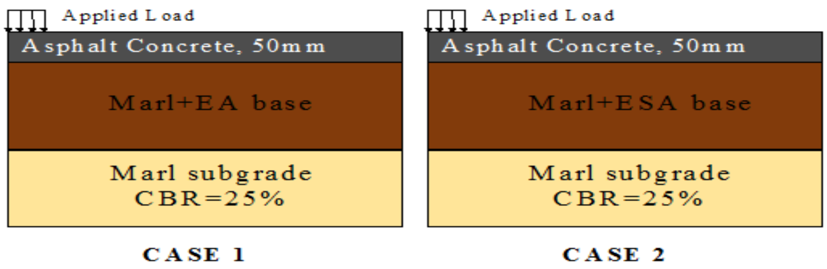


Figure 5.1: Pavement structures on Marl subgrade.

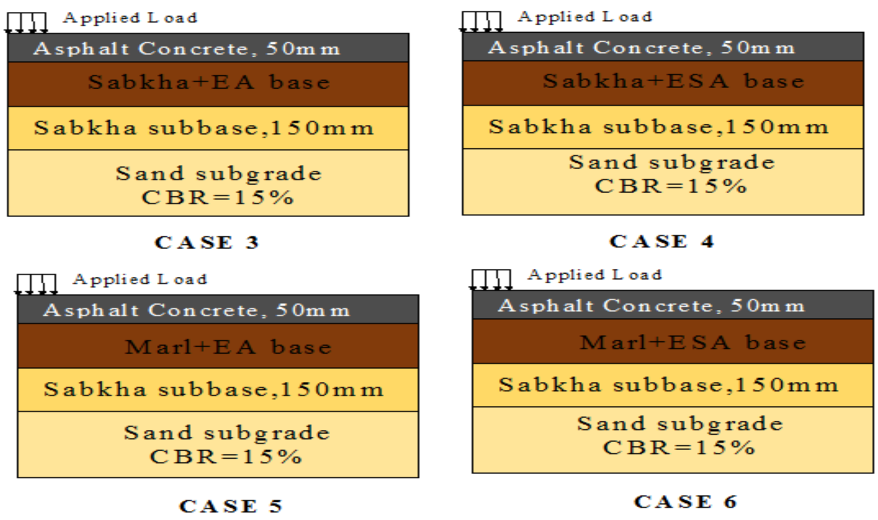


Figure 5.2: Pavement structures on sand subgrade.

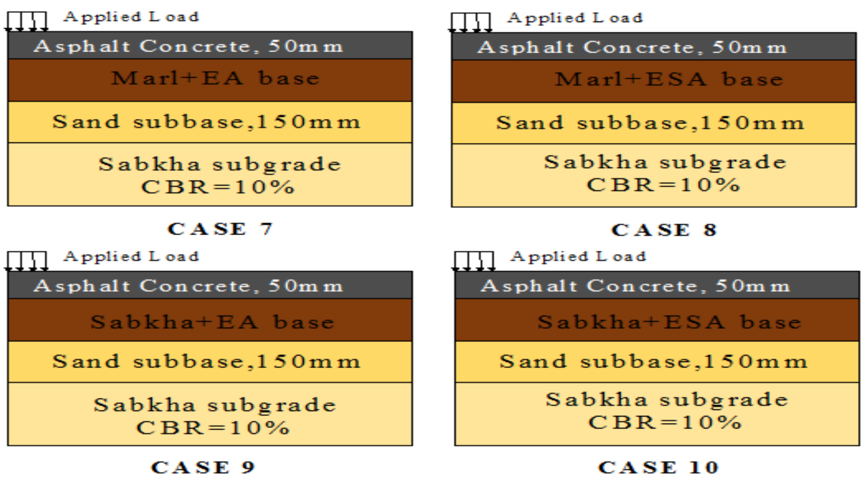


Figure 5.3: Pavement structures on sabkha subgrade.

5.1.2 Traffic Characteristics.

Traffic characteristics are determined in terms of the number of repetitions of 80 kN single-axle load applied to the pavement on two sets of dual tires. The dual tires are represented as two circular plates with a diameter of 11.5cm each and spaced 34.5cm apart. This representation corresponds to a contact pressure of 482.6 kPa [59].

5.1.3 Multilayer Linear Elastic Systems Analyses

The pavement system is subdivided into a number of sub layers. Each sub layer is assigned an initial resilient modulus from resilient modulus test, and a location for stress computations is defined to each one. The 3D-MOVE Analysis, a computer program [56], computes the state of the stress at all locations in each sub layer, averages them, and then computes a new value of the resilient modulus for each sub layer by using the results of resilient modulus test. This analysis continues until the deviation between two consecutive computed resilient modulus is less than 1% in all sub layers.

5.1.4 Pavement Materials' Properties.

Material properties of subgrade layer are normally characterized by CBR test, although predicting the rutting model requires resilient modulus as the input data so CBR values must be converted to resilient modulus. The most widely relation between CBR and resilient modulus used for the subgrade stiffness is the following relations as determined by Heukelom and Klomp [60].

$$M_{R\ (MPa)} = 10.34 \text{ x } CBR, \quad CBR \leq 10\% \tag{5.1}$$

$$M_{R\ (MPa)} = 20.68 \text{ x } CBR^{0.65,} \quad CBR > 10\% \tag{5.2}$$

For base layer, the material properties are normally characterized by resilient modulus which was found after the analysis of the pavement structure as discussed in section 5.1.3.

The proprieties of the asphaltic concrete layer were taken according to Ramadhan [61]. The properties of the asphalt concrete, base, subbase and subgrade are given in Table 5.1.

Table 5.1: Pavement Materials' Properties and Input Parameters values for VESYS5W.

parameters	Subgrade/subbase layer**			Base course lyere						Asphalt layer
	Marl	Sabkha	Sand	Marl		Sabkha		Dune sand		
				EA	ESA	EA	ESA	EA	ESA	
				Three layers pavement structure						
				VESYS Parameters at 22.2^{o}C						
$M_{R(Mpa)}$	166	-----	-----	680	685	-----	-----	-----	-----	2551*
μ	0.07	-----	-----	0.193	0.474	-----	-----	-----	-----	0.70*
α	0.91	-----	-----	0.891	0.891	-----	-----	-----	-----	0.44*
				VESYS Parameters at 40^{o}C						
$M_{R(Mpa)}$	166	-----	-----	627.5	645	-----	-----	-----	-----	1320*
μ	0.07	-----	-----	0.193	0.568	-----	-----	-----	-----	0.64*
α	0.91	-----	-----	0.891	0.916	-----	-----	-----	-----	0.40*
				Four layers pavement structure						
				VESYS Parameters at 22.2^{o}C						
$M_{R(Mpa)}$	-----	110	100	680	685	665	650	-----	-----	2551*
μ	-----	0.20	1.13	0.193	0.474	0.946	0.946	-----	-----	0.70*
α	-----	0.85	0.89	0.891	0.817	0.814	0.814	-----	-----	0.44*
				VESYS Parameters at 40^{o}C						
$M_{R(Mpa)}$	-----	110	100	627.5	645	573	620	-----	-----	1320*
μ	-----	0.20	1.13	0.193	0.568	4.052	0.637	-----	-----	0.64*
α	-----	0.85	0.89	0.891	0.916	0.814	0.814	-----	-----	0.40*
Thickne	Infinity/150mm			Variable		Variable		Variable		100
ν	0.35			0.35		0.35		0.35		0.35

*These values after Ramadhan [61] ,

**Subgrade layer materials were tested at one temperature 22^{o}C

5.1.5 VESYS Rutting Model Results

As explained in Chapter Two, the VESYS model was used to predict the amount of rutting that is expected to occur in a pavement system constructed with the ten pavement structure cases. Inputs needed for VESYS for the bases are discussed in section 5.1.4. To simulate the state of pavement in real life, measurement of temperature was taken from winter (22^{o}C) and summer (40^{o}C).

The typical output generated by VESYS5W for pavement structure on marl subgrade with marl emulsified sulfur asphalt base (case 2) is shown in Figure 5.4 ,while for all pavement structures (case 1 to case 10) is shown in appendix B from Figure B.1 to Figure B.10 where the relationship between base thickness, total traffic and total rut depth is plotted. In general, the total rut decreased with an increasing base thickness for all types of bases. The results produced were similar to the results obtained from the dynamic triaxial test with a large amount of deformation occurring at the start of the test and decreasing thereafter to nearly a constant value.

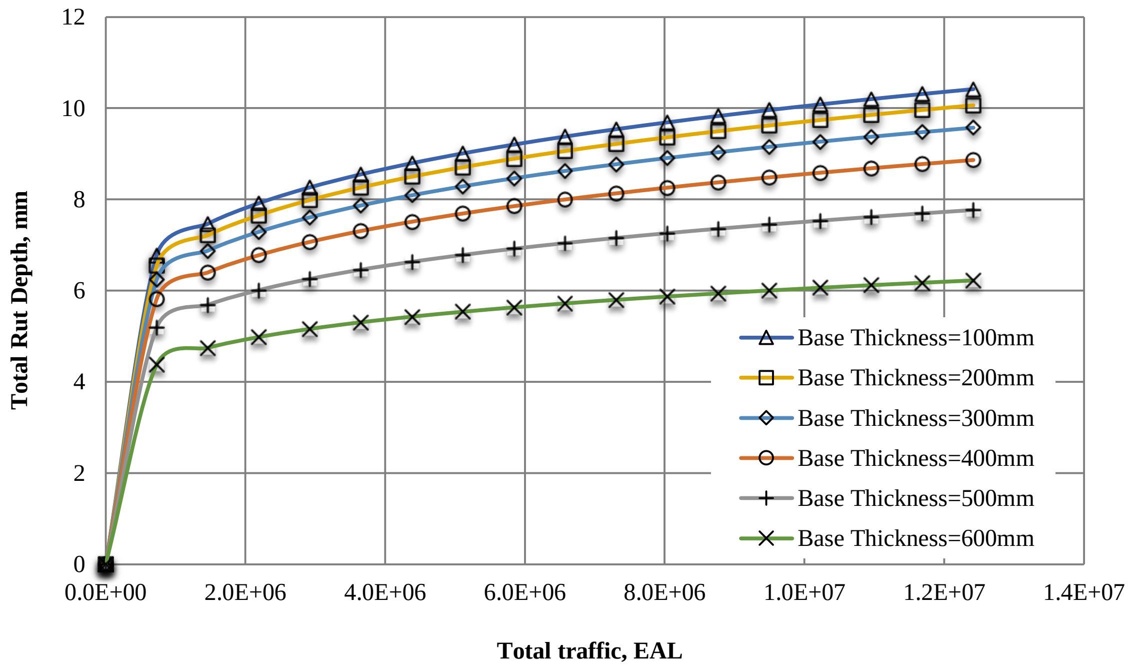


Figure 5.4: Relationship between rut depth, total traffic and base thickness (case 2).

5.2 Pavement Thickness Design Charts

This section describes the application of results of rutting modeling in the design of pavement systems, conducted as described in section 5.1.5, in the design of pavement systems employing EA and ESA with local soils (i.e., marl, sabkha, and dune sand) as base courses. The 25mm rut depth was used as critical (limiting) rutting to compute the limit number of load repetitions from rut depth curves which led to the development of design charts for variable thickness of base between 100mm to 600mm. After, relation between base thickness and design traffic for each rut depth were plotted [62].

Figures 5.5 to 5.14 show allowable pavement lives predicted to achieve a certain rut depth for pavement structure cases. The design charts were developed for two seasons, the first when materials are at 22°C (winter) and the second when materials are at 40°C (summer).

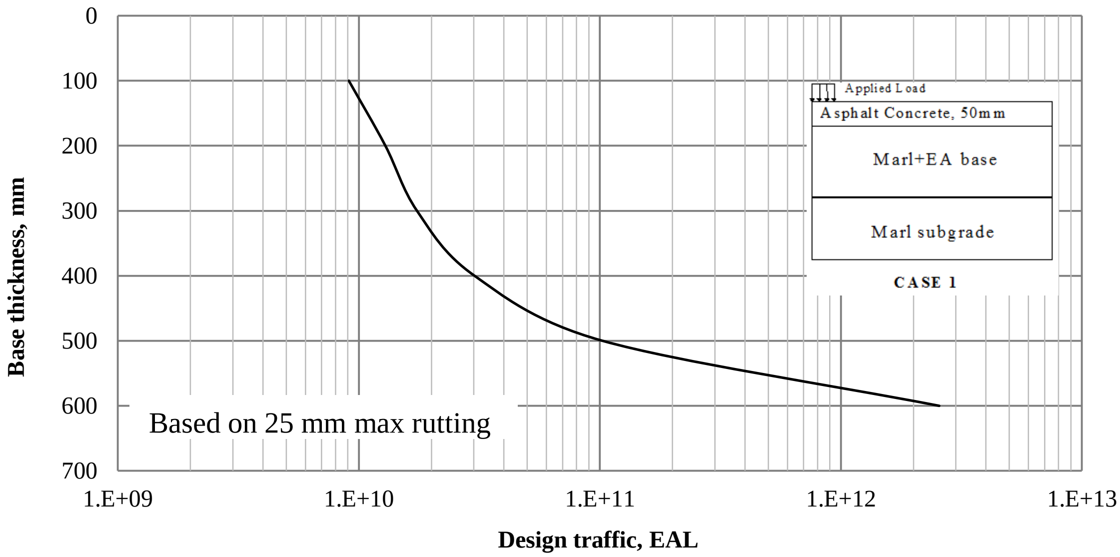


Figure 5.5: Relationship between marl with EA base thickness and total traffic (case 1).

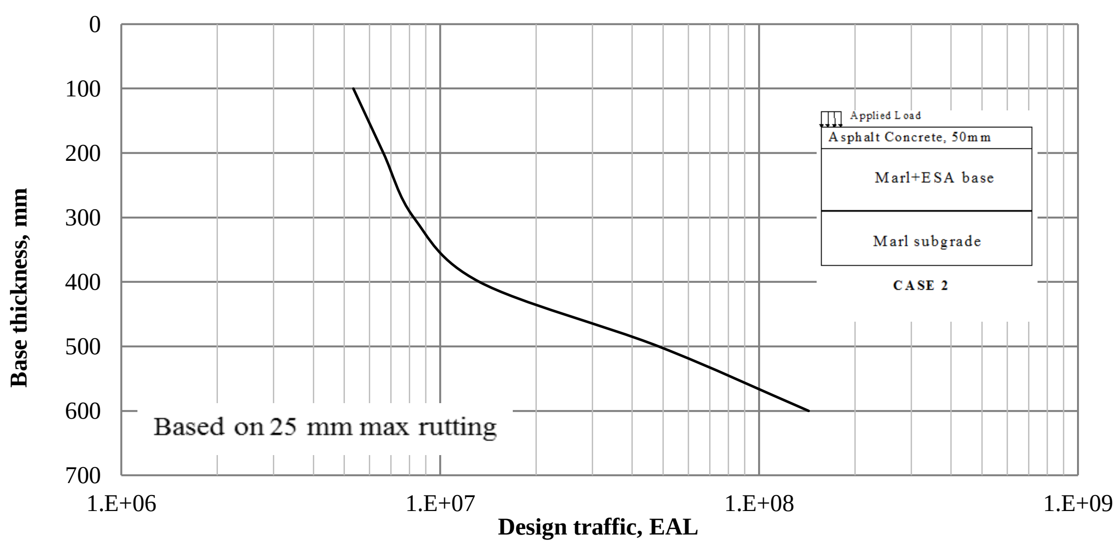


Figure 5.6: Relationship between marl with ESA base thickness and total traffic (case 2).

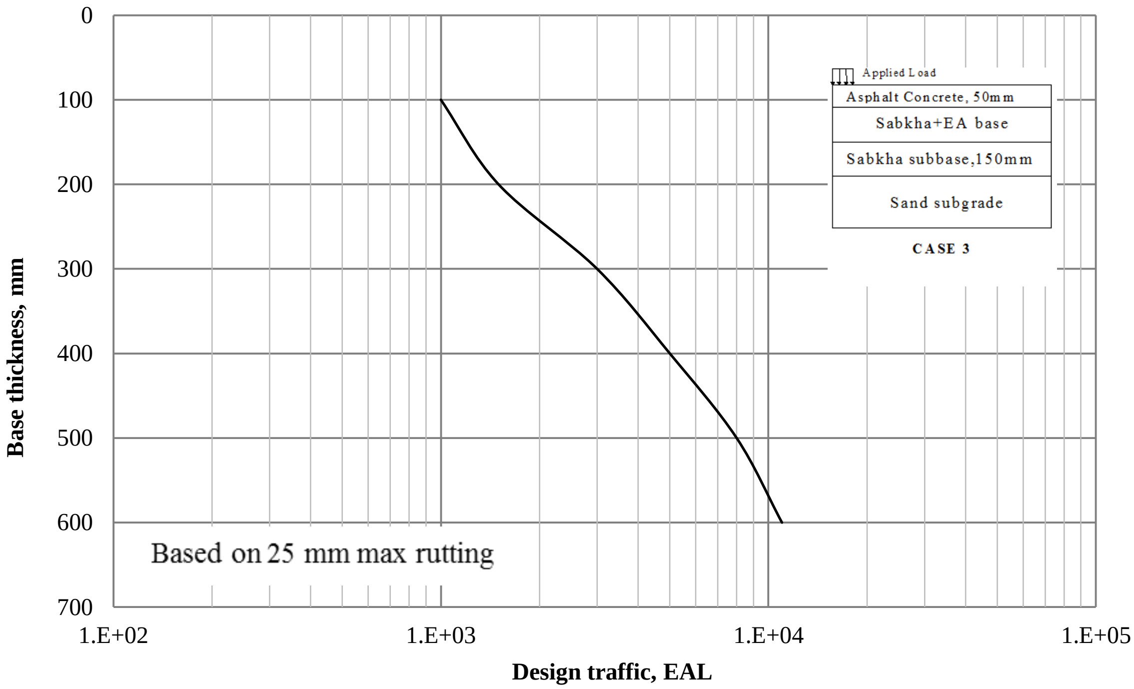


Figure 5.7: Relationship between sabkha with EA base thickness and total traffic (case 3)

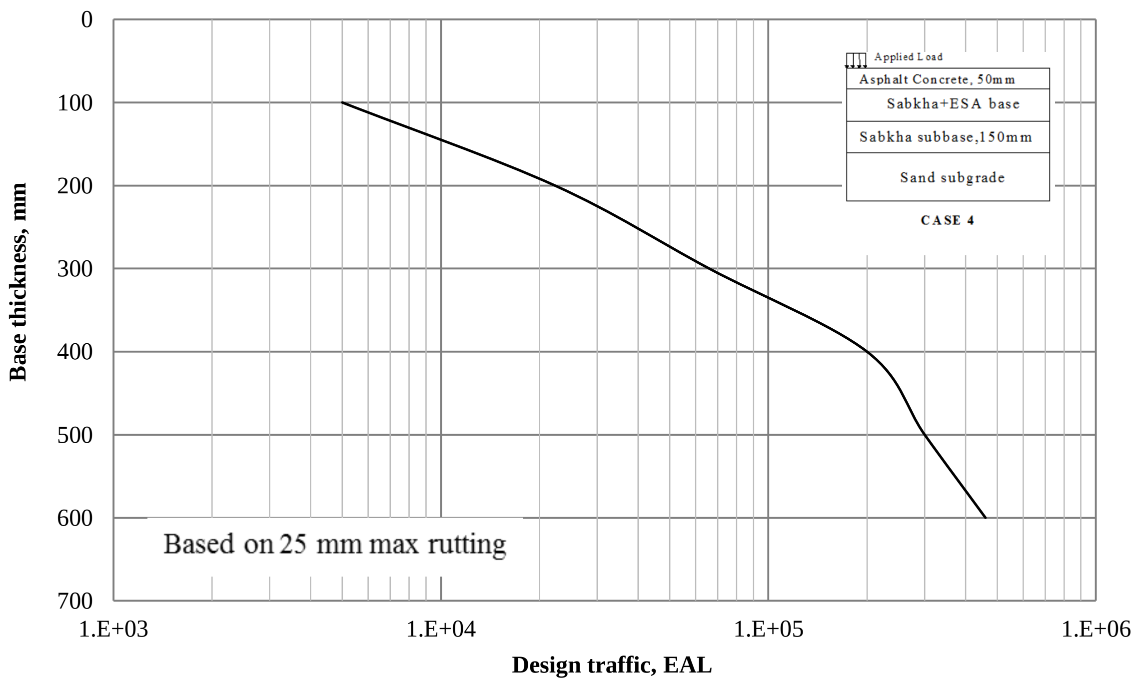


Figure 5.8: Relationship between sabkha with ESA base thickness and total traffic (case 4)

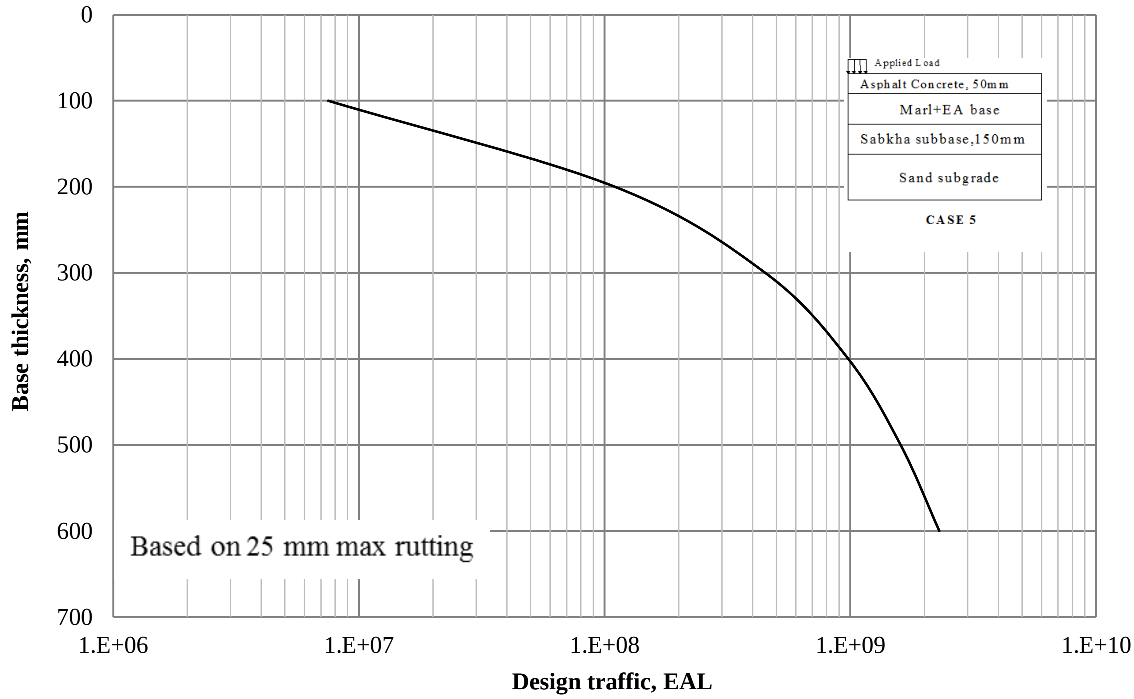


Figure 5.9: Relationship between marl with EA base thickness and total traffic (case 5)

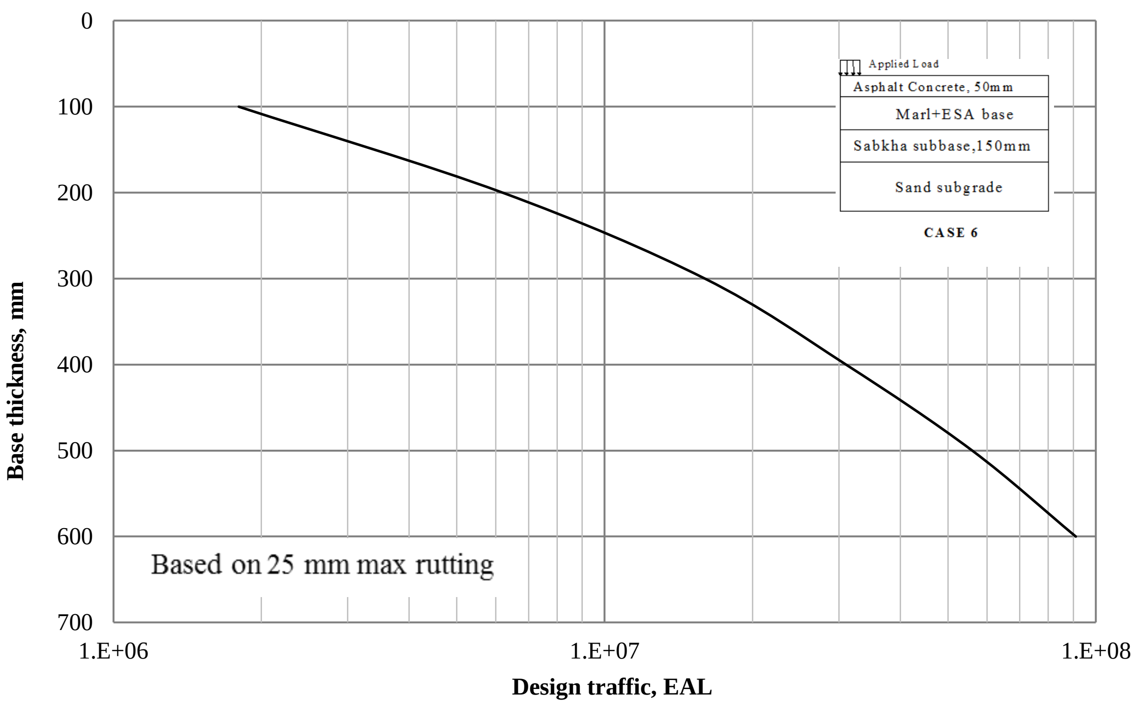


Figure 5.10: Relationship between marl with ESA base thickness and total traffic (case 6)

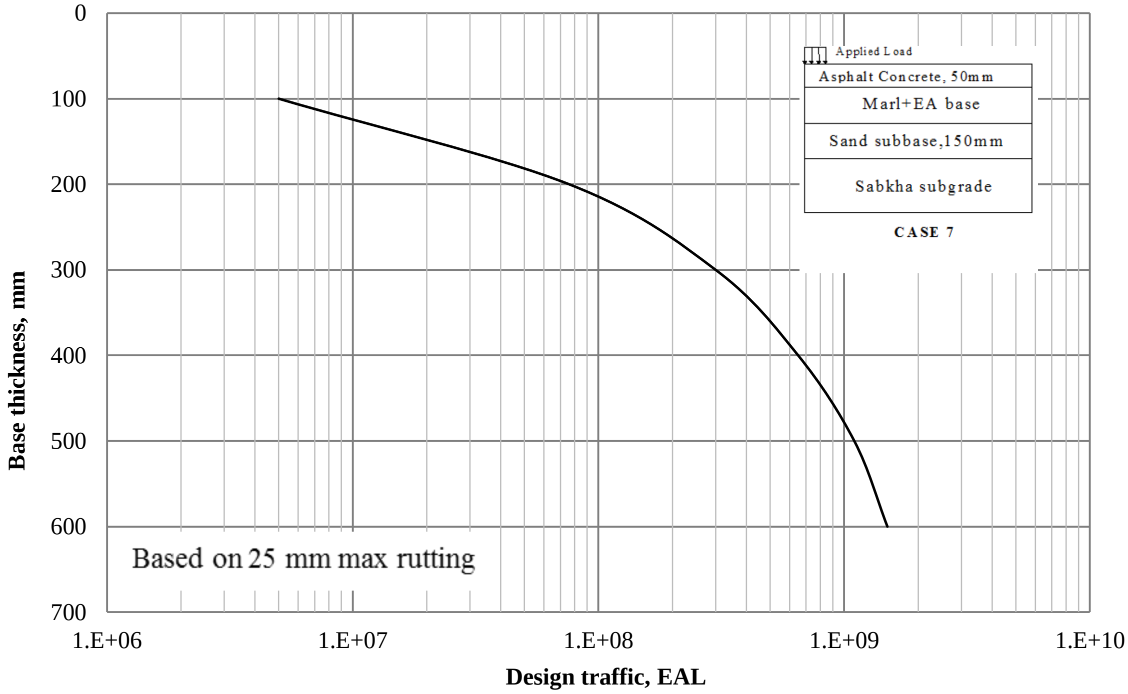


Figure 5.11: Relationship between marl with EA base thickness and total traffic (case 7)

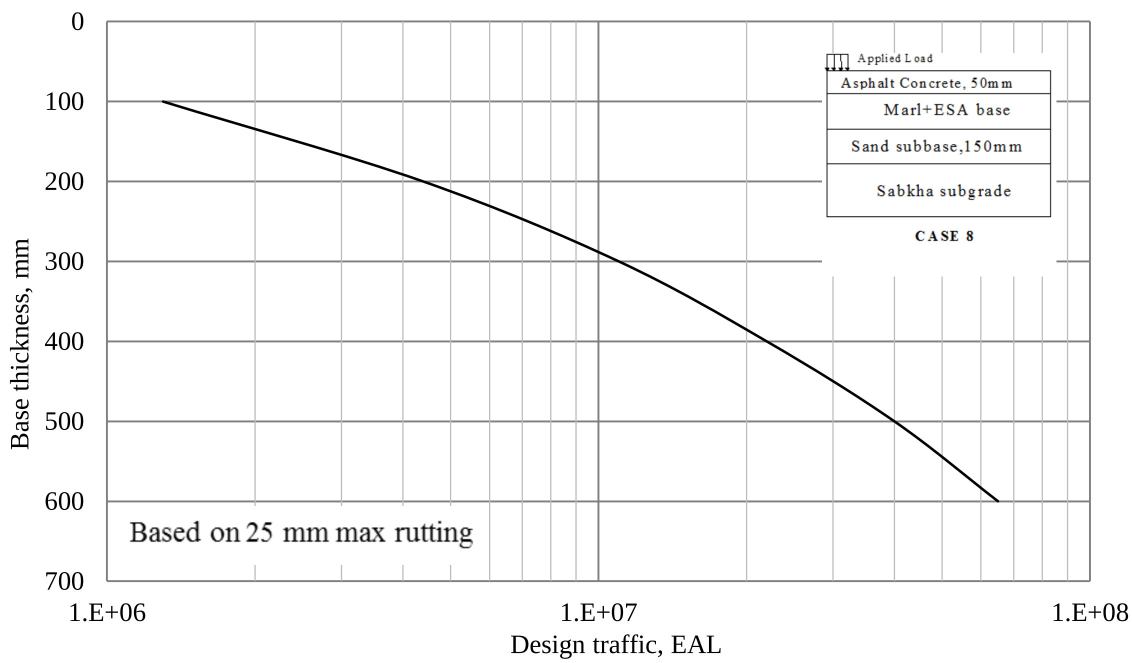


Figure 5.12: Relationship between marl with ESA base thickness and total traffic (case 8)

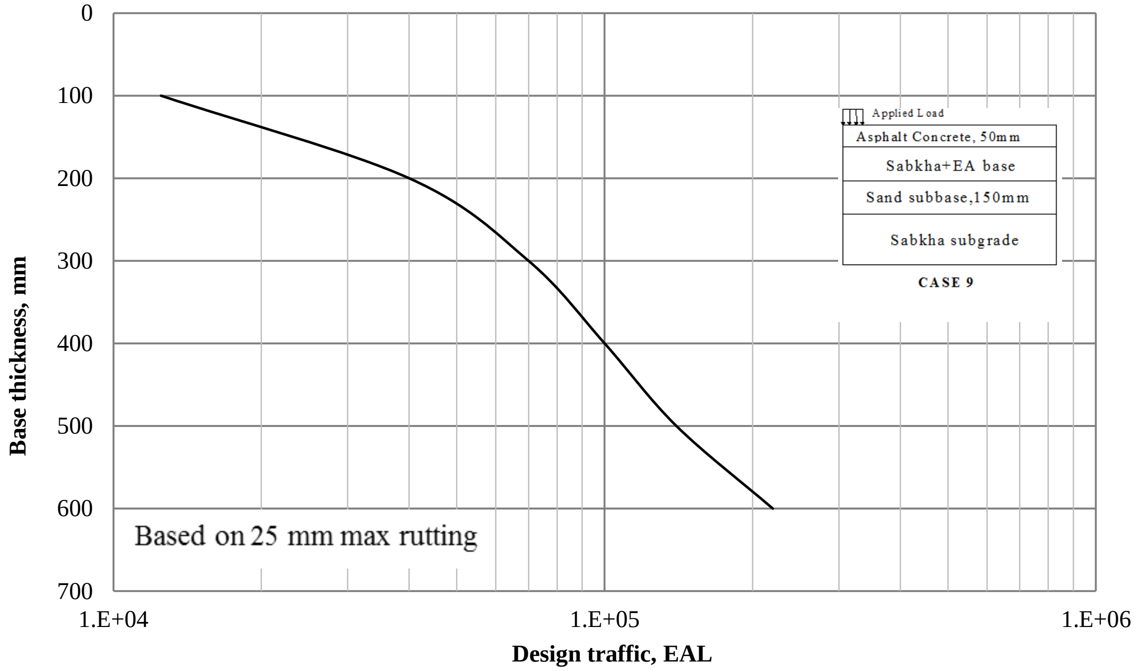


Figure 5.13: Relationship between sabkha with EA base thickness and total traffic (case 9)

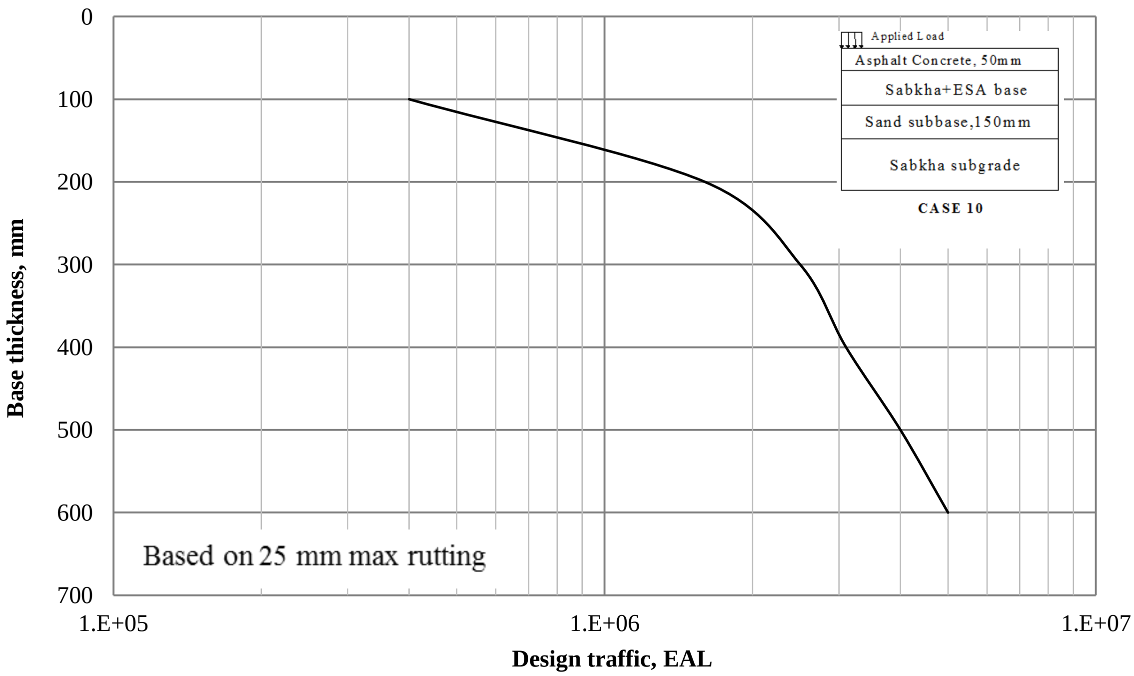


Figure 5.14: Relationship between sabkha with ESA base thickness and total traffic (case 10)

5.3 Summary

This chapter describes an effort to utilize the test results for local field. Material properties were obtained from laboratory experiments and other specifications. The rutting performance of base course was simulated using VESYS model and the results were statistically analyzed. The rutting criteria were used to develop pavement structure design charts. Three local soils (marl, dune sand and sabkha) treated with EA and ESA mixes at different temperature levels (22ºC and 40ºC), were considered for analysis with VESYS5W program. These design charts can be used for local roads in Saudi Arabia.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Summary of the general findings from the study results is presented. Based on the graphical and statistical interpretation of the data obtained from the various tests conducted, the trend and behavior, in which the EA and ESE affect each property of treated marl, sabkha, and dune sand soils, are highlighted.

1. Residual asphalt content has a significant effect on the Marshall Stability as the incorporation of different percentages of EA and ESA have resulted in varying fundamental properties.
2. ESA slightly reduced the value of Marshall Stability for mixtures with sabkha, marl, and dune sand as compared to EA mixes.
3. ESA results in low tensile strength when mixed with marl, sabkha and dune sand.
4. ESA blend shows lower water absorption compared to their EA blend; durability increased when ESA was used as compared to EA.
5. Dune sand did not satisfy the minimum ITS requirements and therefore, it should not use as base for road construction.
6. The addition of ESA to marl, and dune sand causes a drop of the Resilient Modulus except sabkha which exhibits an increase in Resilient Modulus.

7. Values for α decreased with increase in deviator stress because of increase in permanent deformation slop; values of μ increased with increase in deviator stress.
8. The permanent deformation has decreased in sabkha modified with ESA compared to EA treated mixes, while it has increased in marl and dune sand modified with ESA compared to EA treated mixes.
9. VESYS predictions of rut depth follow similar pattern as found in the dynamic triaxial tests.
10. Marl and sabkha with EA or ESA can be used for local road bases/subbases construction.
11. Marl emulsified asphalt mixes and marl emulsified sulfur asphalt mixes tend to withstand higher loads with low rutting (5mm) than dune sand and sabkha with EA and ESA.
12. The rutting criteria were used successfully to develop pavement structure of design charts. These charts can be used for local roads design in Saudi Arabia.

6.2 Recommendations

The results of this research are solely based on laboratory study. It is therefore recommended that the stabilized soils be evaluated for fatigue and rutting under real temperature and traffic to simulate field conditions during service. In this regard, limited controlled field test sections need to be constructed in order to test pavement structure design and performance for final evolution.

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APPENDIX A

MINITAB PRINTOUT

A.1 Marshal Stability

Table A.1: Two-way ANOVA for Dry Marshal Stability for Marl versus % Residual Asphalt. Type of additives

Source	DF	SS	MS	F	P
Type of additives	1	369.835	369.835	372.23	0.000
% Residual Asphalt	5	322.117	64.423	64.84	0.000
Error	5	4.968	0.994		
Total	11	696.920			
S = 0.9968 R-Sq = 99.29% R-Sq(adj) = 98.43%					

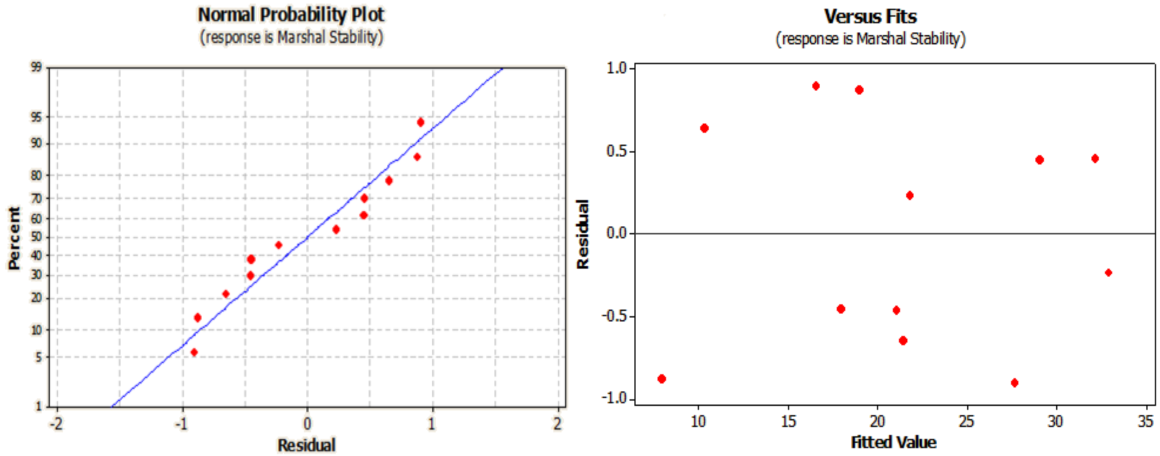

Figure A.1: Normal probability plot and versus fits for Dry Marshal Stability for Marl

Table A.2: Two-way ANOVA for Soaked Marshal Stability for Marl versus % Residual Asphalt. Type of additives

Source	DF	SS	MS	F	P
Type of additives	1	197.381	197.381	136.11	0.000
% Residual Asphalt	5	405.859	81.172	55.98	0.000
Error	5	7.251	1.450		
Total	11	610.491			
S = 1.204 R-Sq = 98.81% R-Sq(adj) = 97.39%					

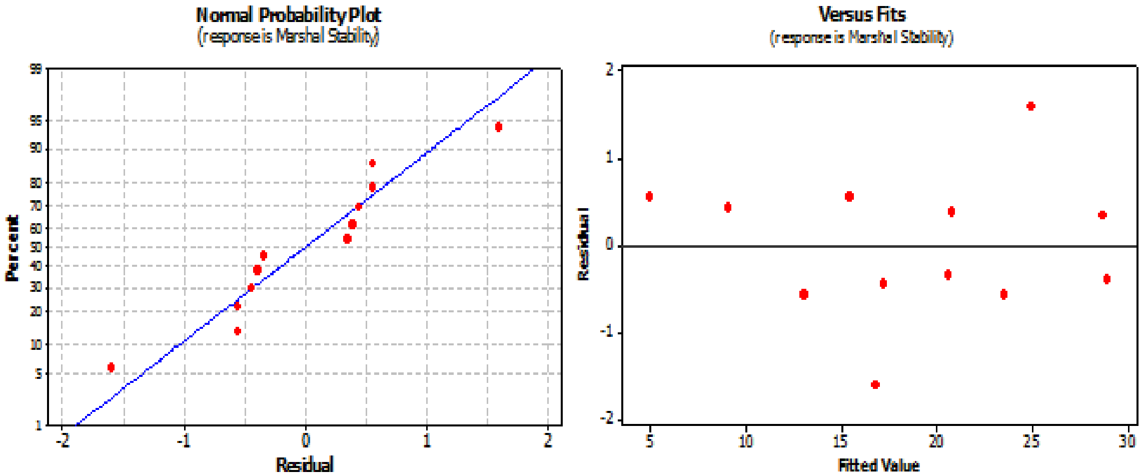

Figure A.2: Normal probability plot and versus fits for Soaked Marshal Stability for Marl

Table A.3: Two-way ANOVA for Dry Marshal Stability for Sabkha versus % Residual Asphalt. Type of additives

Source	DF	SS	MS	F	P
Type of additives	1	6.3289	6.32891	19.74	0.011
% Residual Asphalt	4	11.2387	2.80968	8.76	0.029
Error	4	1.2827	0.32068		
Total	9	18.8503			
S = 0.5663 R-Sq = 93.20% R-Sq(adj) = 84.69%					

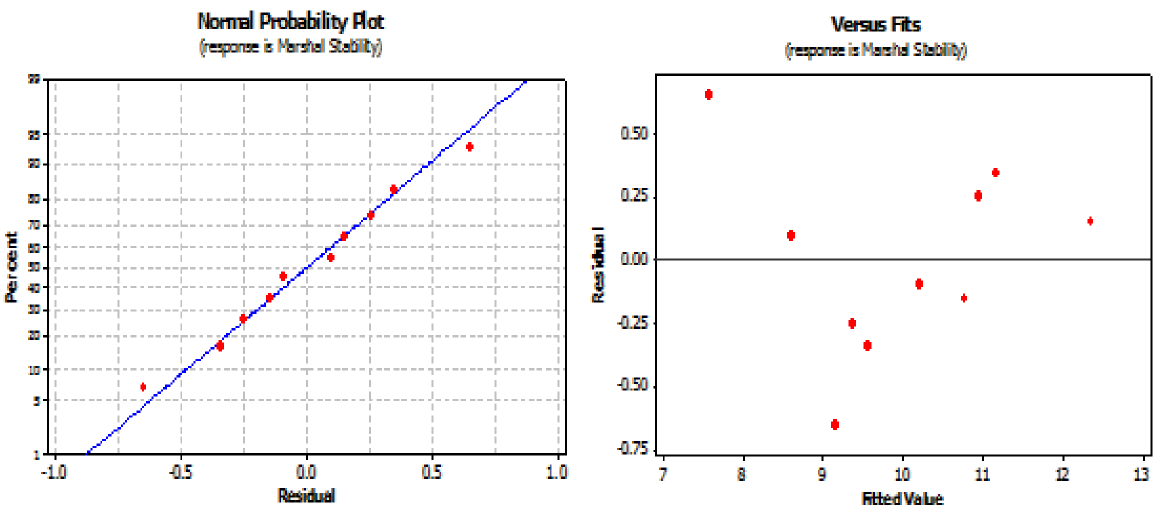

Figure A.3: Normal probability plot and versus fits for dry Marshal Stability for sabkha

Table A.4: Two-way ANOVA for Soaked Marshal Stability for Sabkha versus % Residual Asphalt. Type of additives

Source	DF	SS	MS	F	P
Type of additives	1	0.0400	0.0400	0.18	0.694
% Residual Asphalt	4	9.8198	2.45495	10.99	0.020
Error	4	0.8934	0.22335		
Total	9	10.7533			
S = 0.4726 R-Sq = 91.69% R-Sq(adj) = 81.31%					

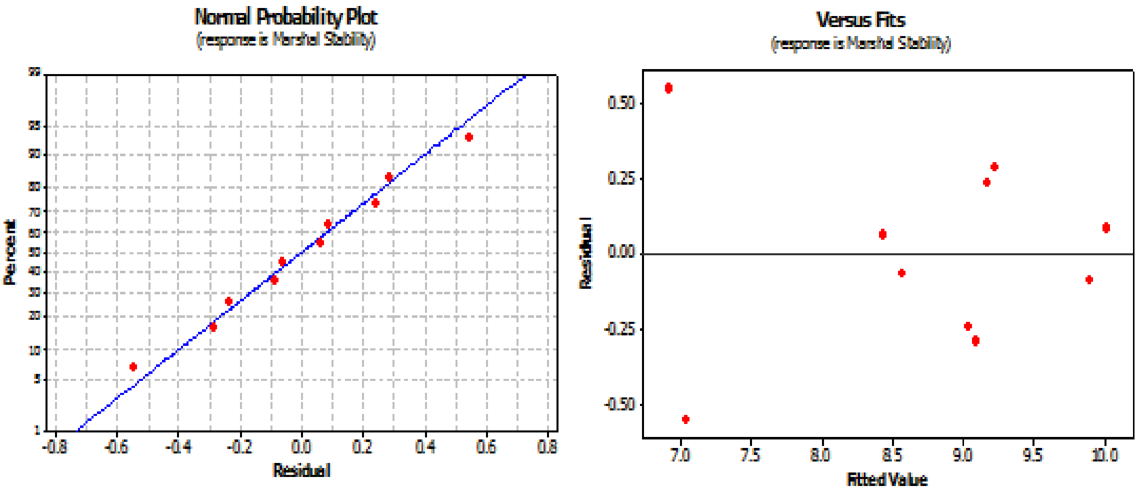

Figure A.4: Normal probability plot and versus fits for Soaked Marshal Stability for sabkha

Table A.5: Two-way ANOVA for Dry Marshal Stability for Dune sand versus % Residual Asphalt. Type of additives

Source	DF	SS	MS	F	P
Type of additives	1	7.9544	7.9544	14.20	0.020
% Residual Asphalt	4	48.8337	12.2084	21.79	0.006
Error	4	2.2412	0.5603		
Total	9	59.0293			
S = 0.7485 R-Sq = 96.20% R-Sq(adj) = 91.46%					

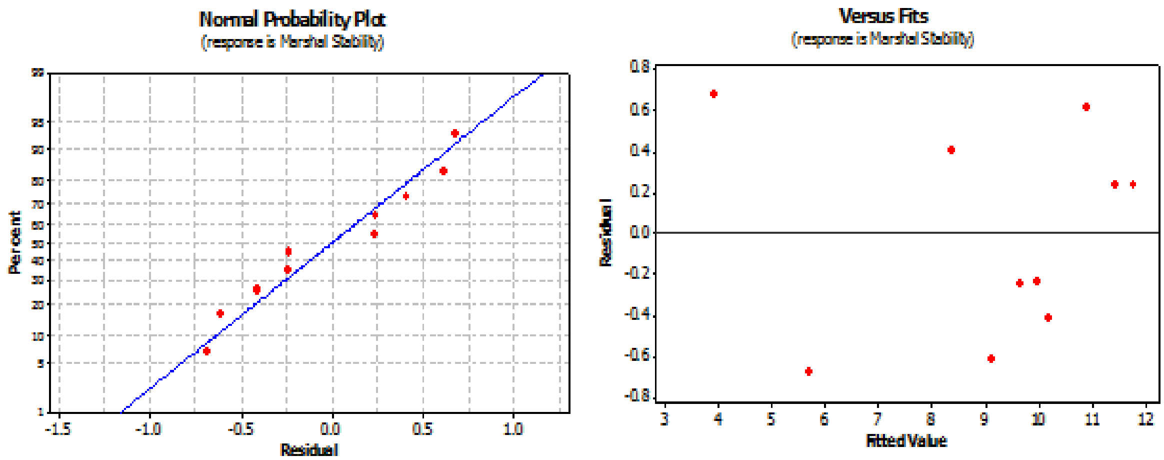

Figure A.5: Normal probability plot and versus fits for dry Marshal Stability for Dune sand

Table A.6: Two-way ANOVA for Soaked Marshal Stability for Dun Sand versus % Residual Asphalt. Type of additives

Source	DF	SS	MS	F	P
Type of additives	1	3.8998	3.8998	4.40	0.104
% Residual Asphalt	4	52.2488	13.0622	14.73	0.012
Error	4	3.5474	0.8869		
Total	9	59.6961			
S = 0.9417 R-Sq = 94.06% R-Sq(adj) = 86.63%					

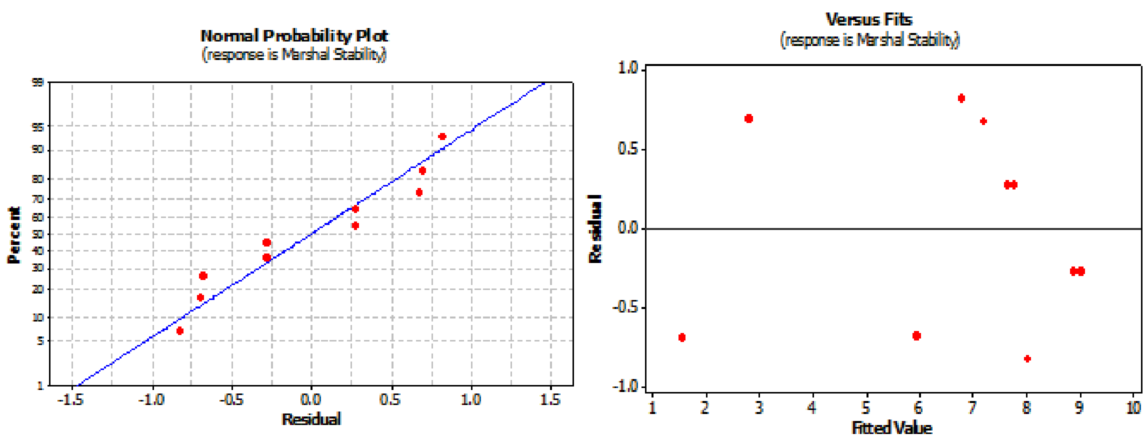

Figure A.6: Normal probability plot and versus fits for soaked Marshal Stability for Dune sand

Table A.7: Two-way ANOVA for Marshal Stability for Marl treatment by EA versus % Residual Asphalt. Effect of water

Source	DF	SS	MS	F	P
Effect of water	1	52.168	52.168	41.78	0.003
% Residual Asphalt	4	357.331	89.3328	71.54	0.001
Error	4	4.995	1.2488		
Total	9	414.494			
S = 1.117 R-Sq = 98.79% R-Sq(adj) = 97.29%					

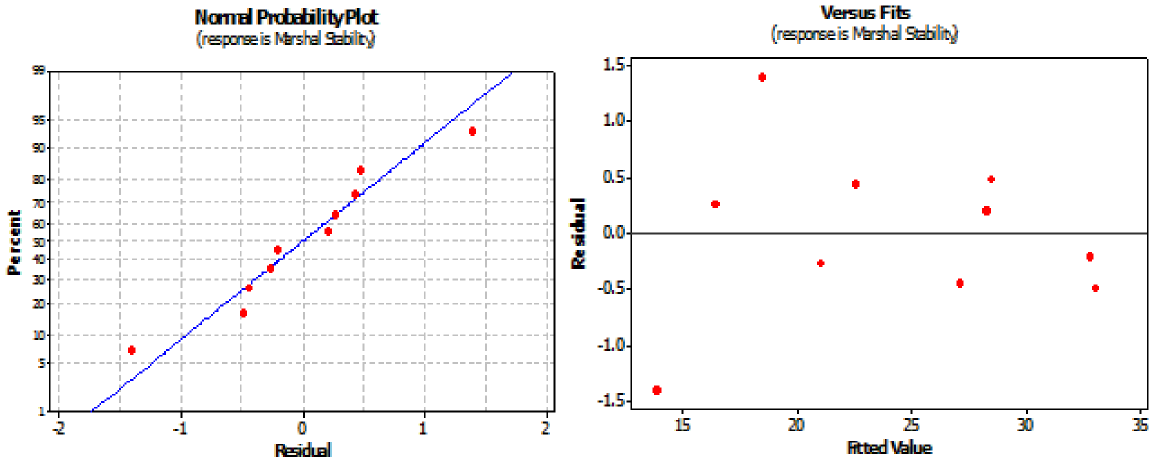

Figure A.7: Normal probability plot and versus fits for Effect of water for marl with EA

Table A.8: Two-way ANOVA for Marshal Stability Marl treatment by ESA versus % Residual Asphalt. Effect of water

Source	DF	SS	MS	F	P
Effect of water	1	3.124	3.124	25.95	0.007
% Residual Asphalt	4	349.194	87.2984	724.98	0.000
Error	4	0.482	0.1204		
Total	9	352.800			
S = 0.3470 R-Sq = 99.86% R-Sq(adj) = 99.69%					

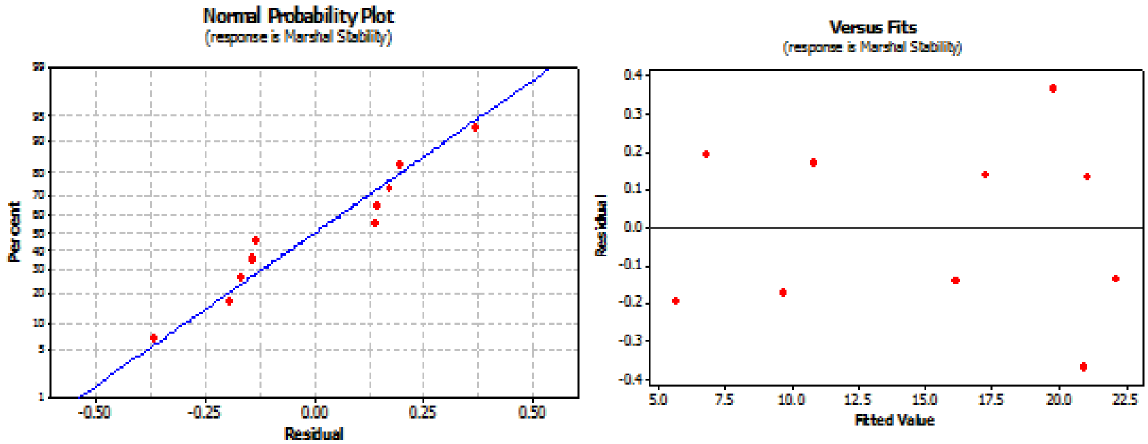

Figure A.8: Normal probability plot and versus fits for Effect of water for marl with ESA

Table A.9: Two-way ANOVA for Marshal Stability for Sabkha treatment by EA versus % Residual Asphalt and Effect of water

Source	DF	SS	MS	F	P
Effect of water	1	9.604	9.604	218.27	0.000
% Residual Asphalt	4	17.056	4.264	96.91	0.000
Error	4	0.176	0.044		
Total	9	26.836			
S = 0.2098 R-Sq = 99.34% R-Sq(adj) = 98.52%					

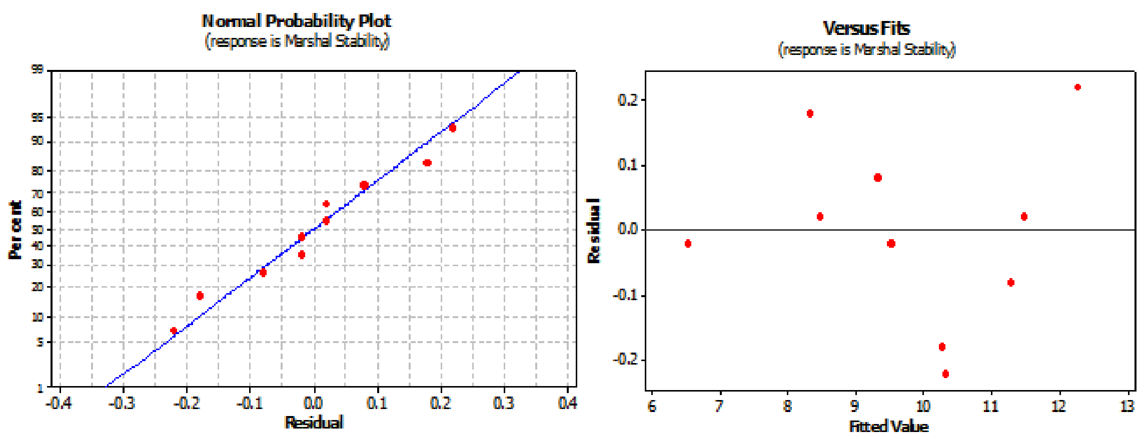

Figure A.9: Normal probability plot and versus fits for Effect of water for sabkha with EA

Table A.10: Two-way ANOVA for Marshal Stability for Sabkha treatment by ESA versus % Residual Asphalt and Effect of water

Source	DF	SS	MS	F	P
Effect of water	1	0.61375	0.61375	16.67	0.015
% Residual Asphalt	4	5.85537	1.46384	39.76	0.002
Error	4	0.14727	0.03682		
Total	9	6.61639			
S = 0.1919 R-Sq = 97.77% R-Sq(adj) = 94.99%					

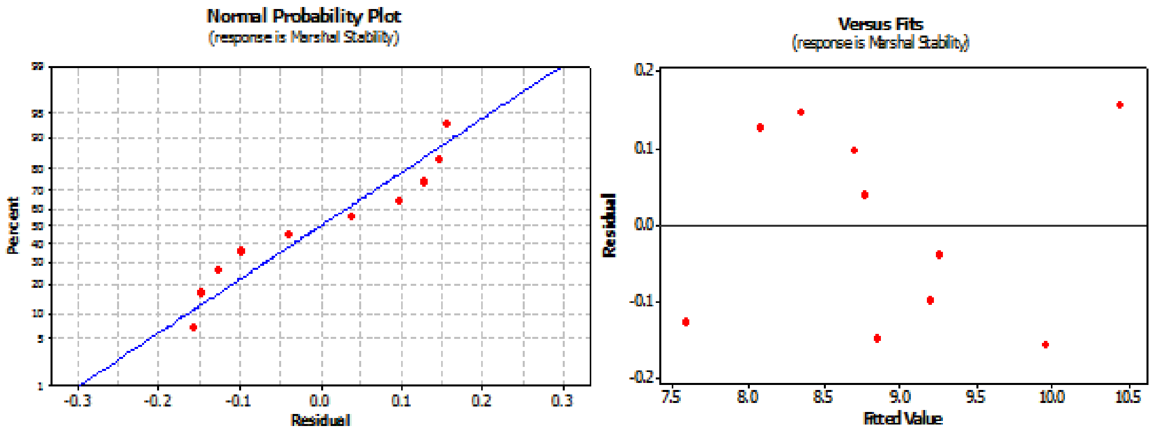

Figure A.10: Normal probability plot and versus fits for Effect of water for sabkha with ESA

Table A.11: Two-way ANOVA for Marshal Stability for Dune sand treatment by EA versus % Residual Asphalt and Effect of water

Source	DF	SS	MS	F	P
Effect of water	1	41.074	41.074	1045.61	0.000
% Residual Asphalt	4	71.009	17.7523	451.92	0.000
Error	4	0.157	0.0393		
Total	9	112.240			
S = 0.1982 R-Sq = 99.86% R-Sq(adj) = 99.69%					

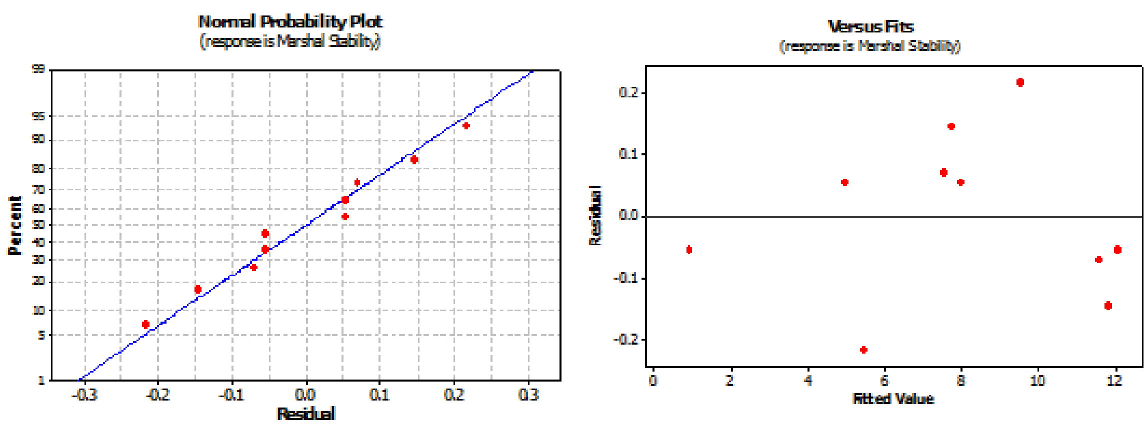

Figure A.11: Normal probability plot and versus fits for Effect of water for sand with EA

Table A.12: Two-way ANOVA for Marshal Stability for Sand treatment by ESA versus % Residual Asphalt and Effect of water

Source	DF	SS	MS	F	P
Effect of water	1	2.6042	2.60418	143.03	0.000
% Residual Asphalt	4	35.6320	8.90800	489.26	0.000
Error	4	0.0728	0.01821		
Total	9	38.3090			
S = 0.1349 R-Sq = 99.81% R-Sq(adj) = 99.57%					

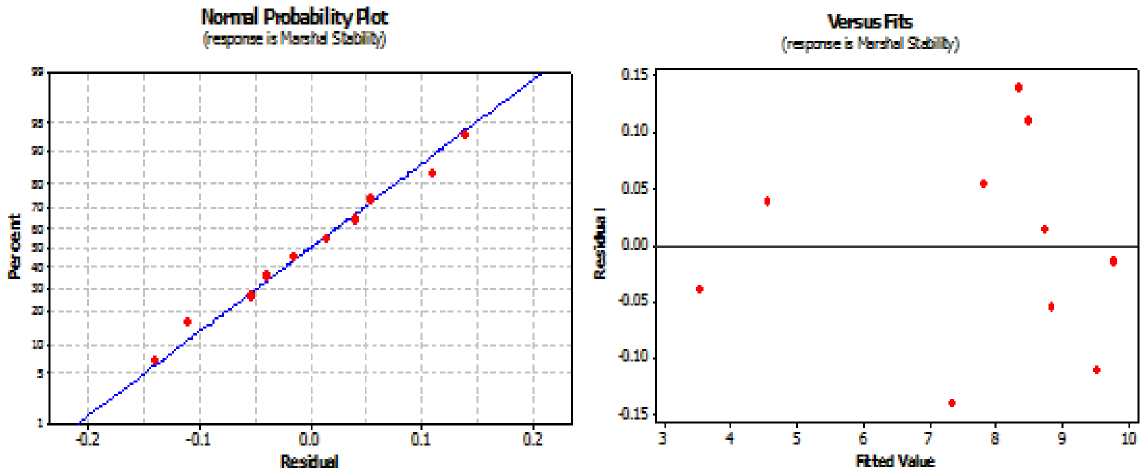

Figure A.12: Normal probability plot and versus fits for Effect of water for sand with ESA

A.2 Indirect Tensile strength

Table A.13: Two-way ANOVA for Indirect Tensile strength for Marl versus % Residual Asphalt and Type of additive

Source	DF	SS	MS	F	P
Type of additives	1	73433	73433.4	14.01	0.013
% Residual Asphalt	5	202184	40436.7	7.71	0.021
Error	5	26212	5242.4		
Total	11	301829			
S = 72.40 R-Sq = 91.32% R-Sq(adj) = 80.89%					

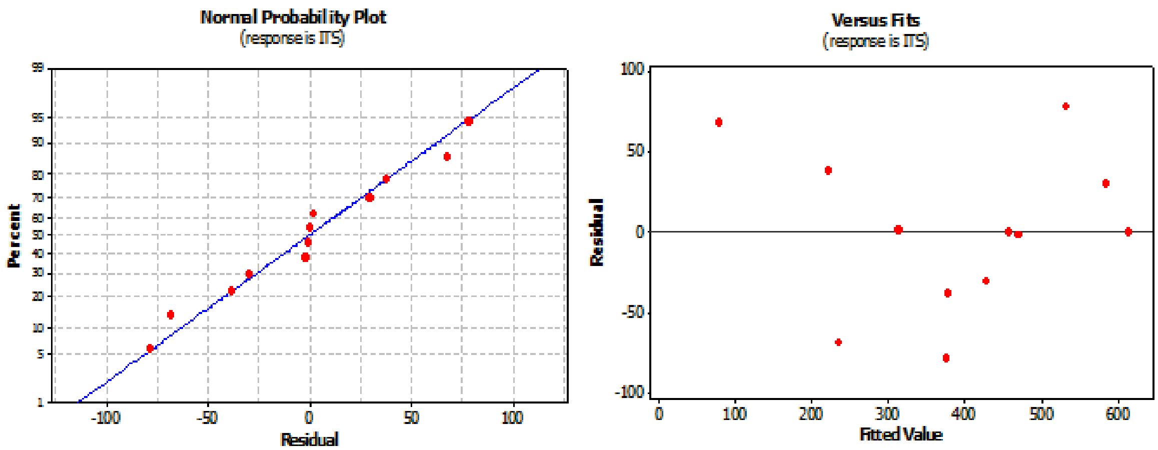

Figure A.13: Normal probability plot and versus fits for Indirect Tensile strength for marl

Table A.14: Two-way ANOVA for Tensile strength for Sabkha versus % Residual Asphalt and Type of additive

Source	DF	SS	MS	F	P
Type of additives	1	35548.9	35548.9	38.57	0.003
% Residual Asphalt	4	30627.1	7656.8	8.31	0.032
Error	4	3686.3	921.6		
Total	9	69862.2			
S = 30.36 R-Sq = 94.72% R-Sq(adj) = 88.13%					

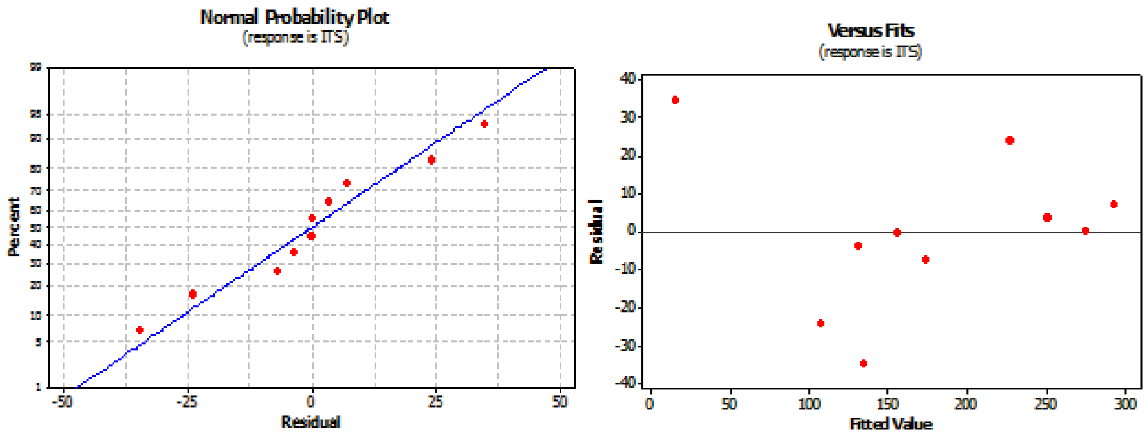

Figure A.14: Normal probability plot and versus fits for Indirect Tensile strength for sabkha

Table A.15: Two-way ANOVA for Tensile strength for Dune sand versus % Residual Asphalt and Type of additive

Source	DF	SS	MS	F	P
Type of additives	1	15429.0	15429.0	52.19	0.002
% Residual Asphalt	4	6929.6	1732.4	5.86	0.058
Error	4	1182.5	295.6		
Total	9	23541.1			
S = 17.19 R-Sq = 94.98% R-Sq(adj) = 88.70%					

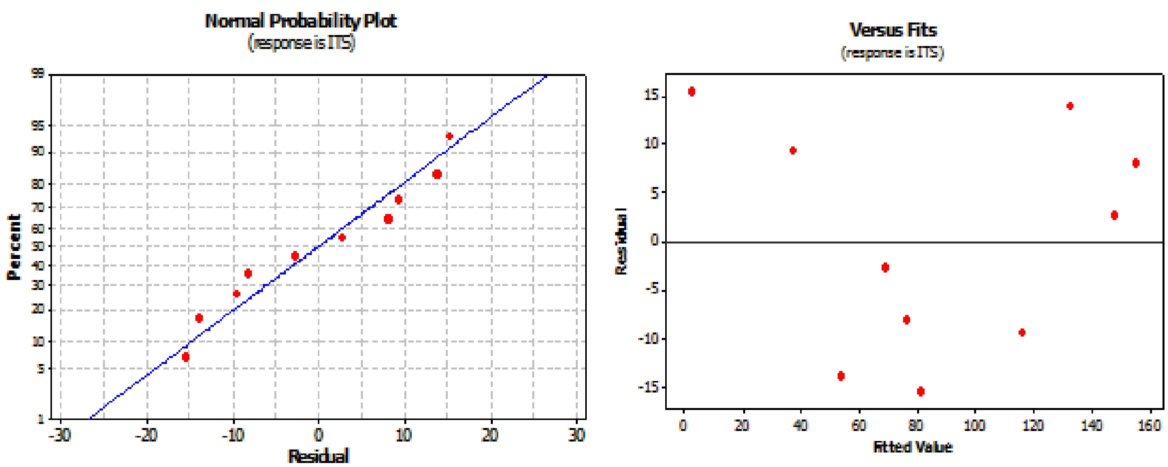

Figure A.15: Normal probability plot and versus fits for Indirect Tensile strength for dune sand

A.3 Resilient Modulus

Table A.16 General Linear Model for M_R for Marl versus Type of additives, Confining Pressure, Deviator stress, and Temperature

Factor	Type		Levels	Values		
Temperature	fixed		2	1, 2		
Type of additives	fixed		2	1, 2		
Confining Pressure	fixed		5	1, 2, 3, 4, 5		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for Resilient Modules, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Temperature	1	34683	34683	34683	4.18	0.045
Type of additives	1	4437	4437	4437	0.54	0.467
Confining Pressure	4	3036363	1203792	300948	36.30	0.000
Deviator stress	4	5539614	5539614	1384903	167.04	0.000
Error	65	538899	538899	8291		
Total	75	9153995				
S = 91.0536 R-Sq = 94.11% R-Sq(adj) = 93.21%						

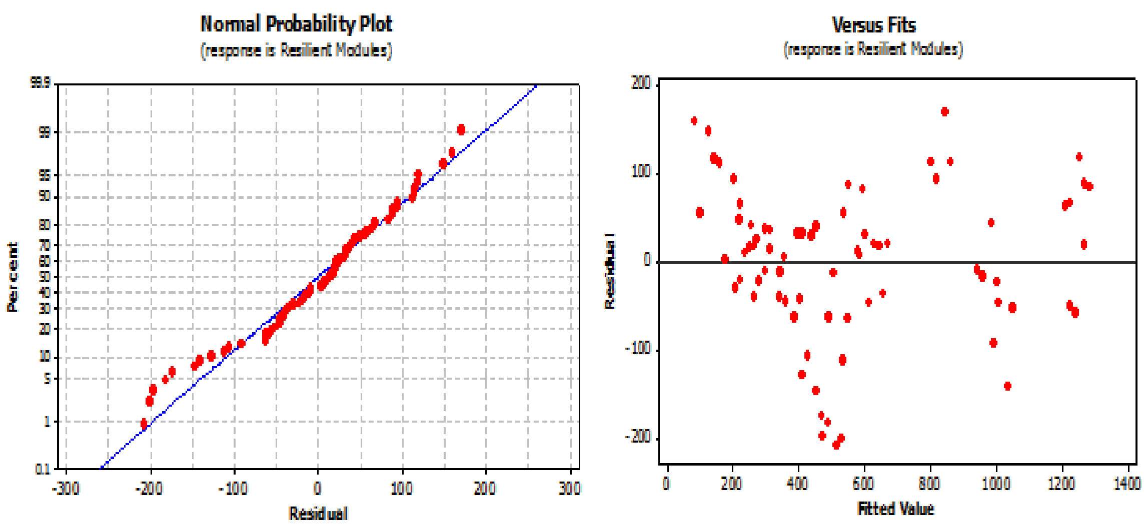

Figure A.16: Normal probability plot and versus fits for M_R for marl

Table A.17: General Linear Model for M_R for Sabkha versus Type of additives, Confining Pressure, Deviator stress, and Temperature

Factor	Type		Levels	Values		
Temperature	fixed		2	1, 2		
Type of additives	fixed		2	1, 2		
Confining Pressure	fixed		5	1, 2, 3, 4, 5		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for Resilient Modules, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Temperature	1	45786	45786	45786	7.18	0.009
Type of additives	1	8096	8096	8096	1.27	0.264
Confining Pressure	4	2491726	992919	248230	38.94	0.000
Deviator stress	4	4577084	4577084	1144271	179.51	0.000
Error	65	414346	414346	6375		
Total	75	7537038				
S = 79.8408 R-Sq = 94.50% R-Sq(adj) = 93.66%						

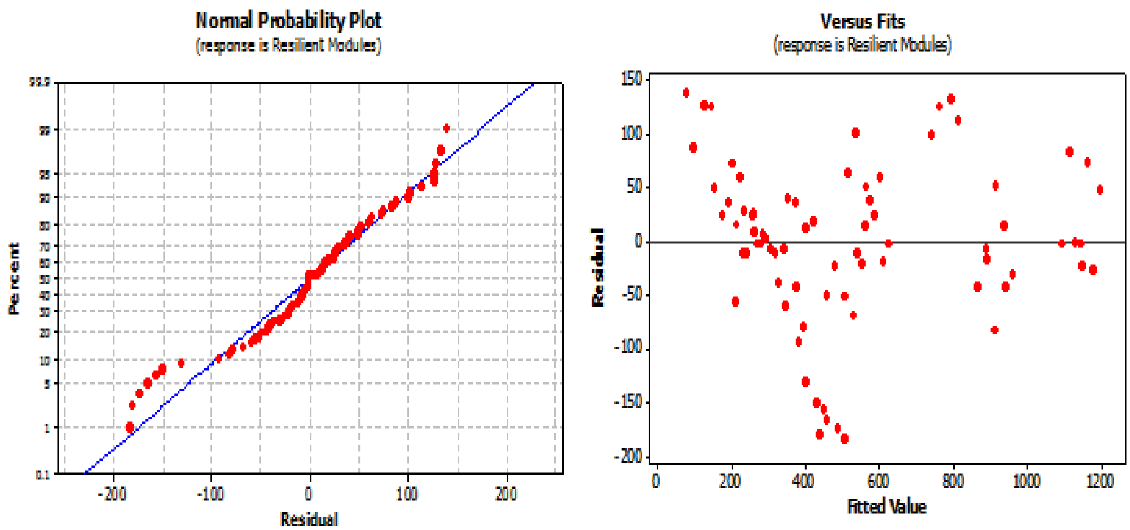

Figure A.17: Normal probability plot and versus fits for M_R for sabkha

Table A.18: General Linear Model for M_R for Dune sand versus Type of additives, Confining Pressure, Deviator stress, and Temperature

Factor	Type		Levels	Values		
Temperature	fixed		2	1, 2		
Type of additives	fixed		2	1, 2		
Confining Pressure	fixed		5	1, 2, 3, 4, 5		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for Resilient Modules, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Temperature	1	9186	9186	9186	3.43	0.023
Type of additives	1	875	875	875	0.14	0.713
Confining Pressure	4	2458993	992665	248166	38.65	0.000
Deviator stress	4	4054373	4054373	1013593	157.88	0.000
Error	65	417305	417305	6420		
Total	75	6940732				
S = 80.1254 R-Sq = 93.99% R-Sq(adj) = 93.06%						

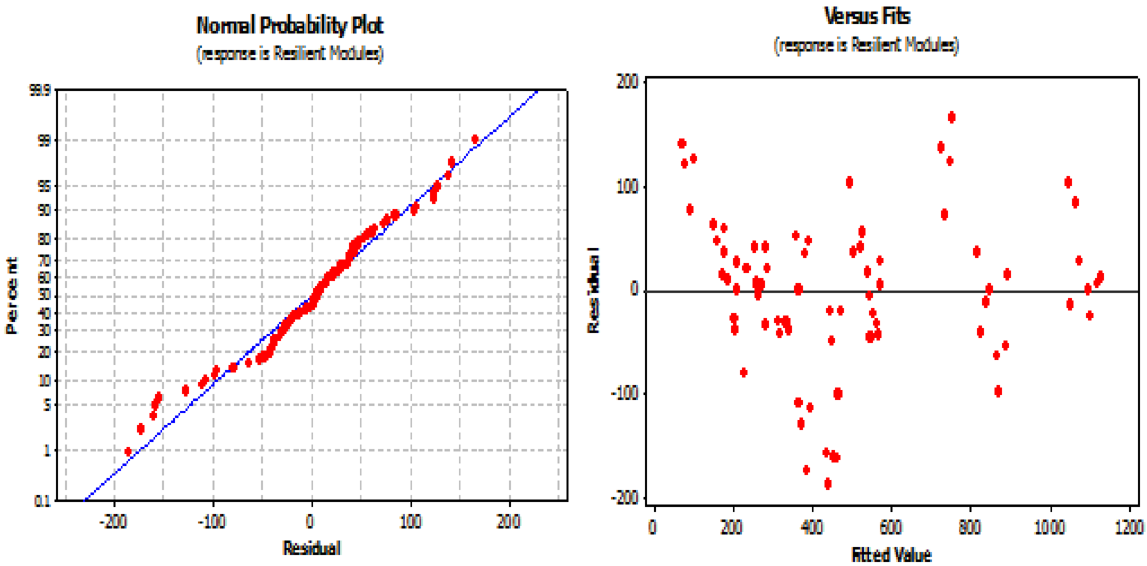

Figure A.18: Normal probability plot and versus fits for M_R for dune sand

Table A.19: General Regression Analysis for M_R versus Type if soils, Type of additives, Confining Pressure, Deviator stress, and Temperature

Regression Equation				
Resilient Modules = 166.616 - 2.10745 Temperature - 35.8428 Type of SOIL + 9.71308 Type of additives - 0.245712 Confining Pressure + 4.20873 Deviator stress				
Term Coefficients	Coef	SE Coef	T	P
Constant	166.616	16.4099	10.1534	0.000
Temperature	-2.107	0.3237	-6.5107	0.000
Type of SOIL	-35.843	3.5680	-10.0457	0.000
Type of additives	9.713	5.8264	1.6671	0.097
Confining Pressure	-0.246	0.0805	-3.0507	0.003
Deviator stress	4.209	0.0456	92.2599	0.000
Summary of Model				
S = 43.9887 R-Sq = 98.20% R-Sq(adj) = 98.16% PRESS = 454965 R-Sq(pred) = 98.09%				

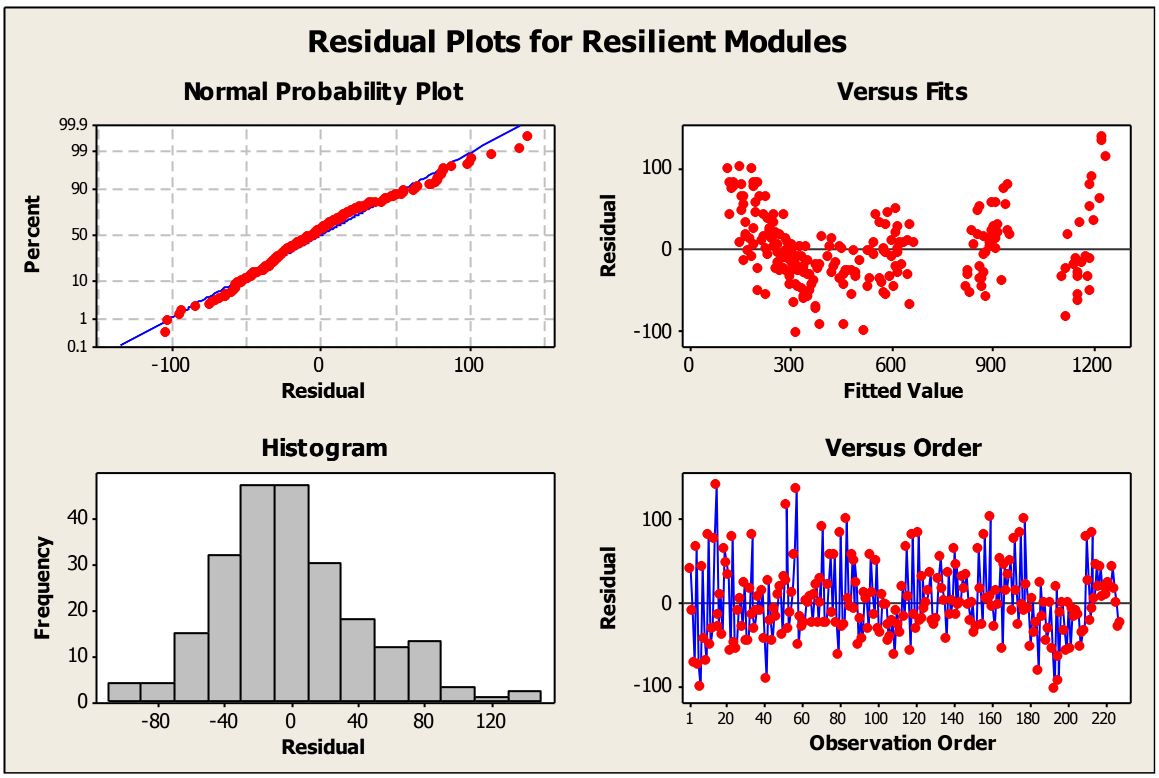

Figure A.19: Residual plot for M_R versus Type if soils, Type of additives, Confining Pressure, Deviator stress, and Temperature

A.4 Rutting parameters µ, α, Rutting intercept (a) and slop (b)

Table A.20: General Linear Model for µ versus Type of additives, Temperature and Deviator stress for Marl soil

Factor	Type		Levels	Values		
Type of additives	fixed		2	1, 2		
Temperature	fixed		2	1, 2		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for µ, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of additives	1	4.11180	3.90086	3.90086	57.53	0.000
Temperature	1	0.01299	0.03630	0.03630	0.54	0.485
Deviator stress	4	0.42314	0.42314	0.10578	1.56	0.274
Error	8	0.54244	0.54244	0.06780		
Total	14	5.09036				
S = 0.260393 R-Sq = 89.34% R-Sq(adj) = 81.35%						

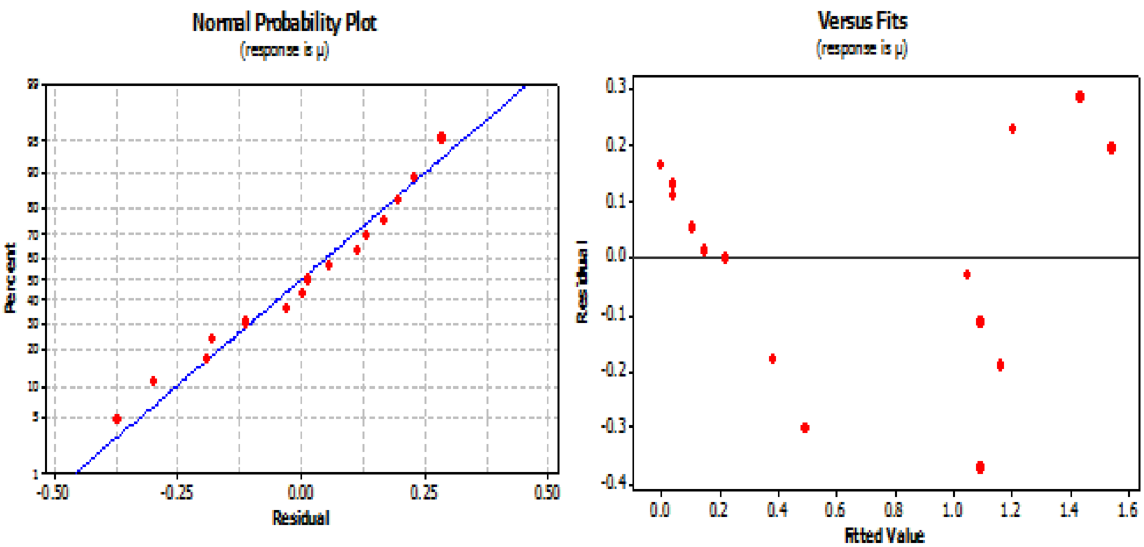

Figure A.20: Normal probability plot and versus fits for µ for marl

Table A.21: General Linear Model for μ versus Type of additives, Temperature and Deviator stress for Sabkha soil

Factor	Type		Levels	Values		
Type of additives	fixed		2	1, 2		
Temperature	fixed		2	1, 2		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for μ, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of additives	1	0.2836	0.2836	0.2836	0.87	0.374
Temperature	1	2.9904	1.9120	1.9120	5.89	0.038
Deviator stress	4	1.5160	1.5160	0.3790	1.17	0.387
Error	9	2.9223	2.9223	0.3247		
Total	15	7.7123				
S = 0.569826 R-Sq = 62.11% R-Sq(adj) = 36.85%						

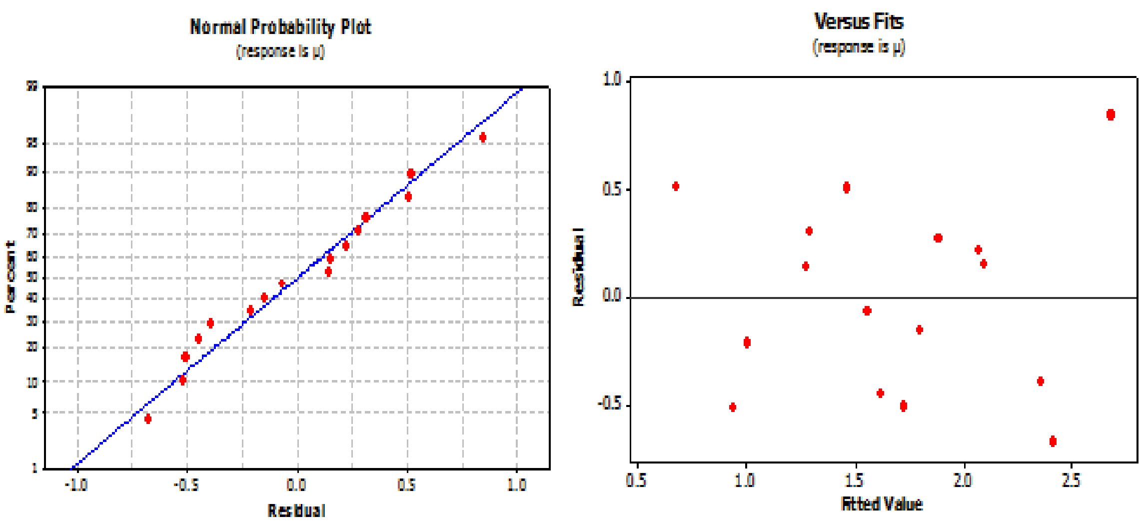

Figure A.21: Normal probability plot and versus fits for μ for sabkha

Table A.22: General Linear Model for μ versus Type of additives, Temperature and Deviator stress for Dune sand soil

Factor	Type		Levels	Values		
Type of additives	fixed		2	1, 2		
Temperature	fixed		2	1, 2		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for μ, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of additives	1	0.77411	0.67321	0.67321	7.95	0.023
Temperature	1	0.23636	0.39603	0.39603	4.68	0.063
Deviator stress	4	0.39112	0.39112	0.09778	1.15	0.398
Error	8	0.67761	0.67761	0.08470		
Total	14	2.07920				
S = 0.291035 R-Sq = 67.41% R-Sq(adj) = 42.97%						

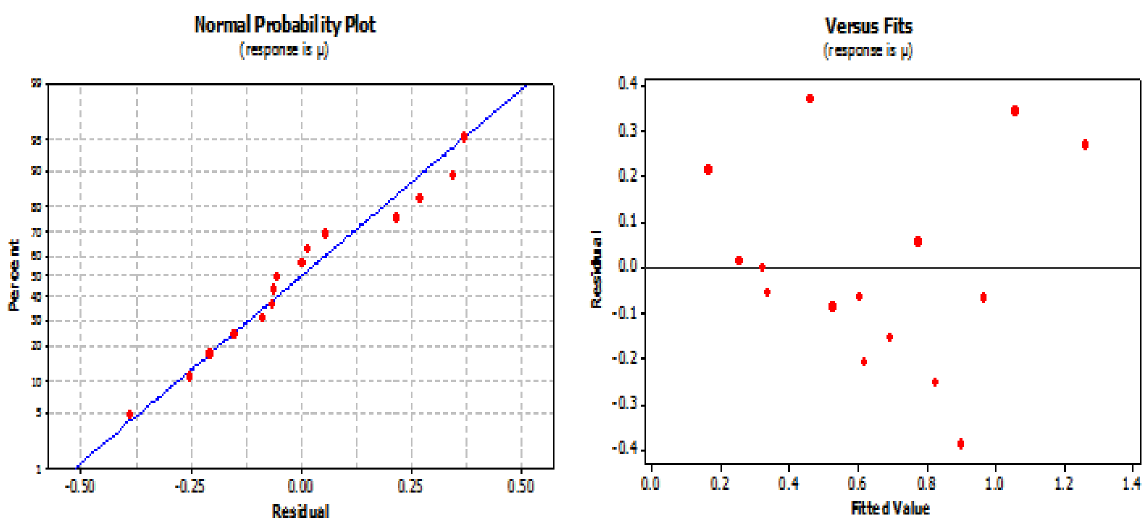

Figure A.22: Normal probability plot and versus fits for μ for dune sand

Table A.23: General Linear Model for α versus Type of additives, Temperature and Deviator stress for Marl soil

Factor	Type		Levels	Values		
Type of additives	fixed		2	1, 2		
Temperature	fixed		2	1, 2		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for α, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of additives	1	0.0005186	0.0010286	0.0010286	1.40	0.271
Temperature	1	0.0033931	0.0040333	0.0040333	5.48	0.047
Deviator stress	4	0.0034403	0.0034403	0.0008601	1.17	0.393
Error	8	0.0058881	0.0058881	0.0007360		
Total	14	0.0132400				
S = 0.0271295 R-Sq = 55.53% R-Sq(adj) = 22.17%						

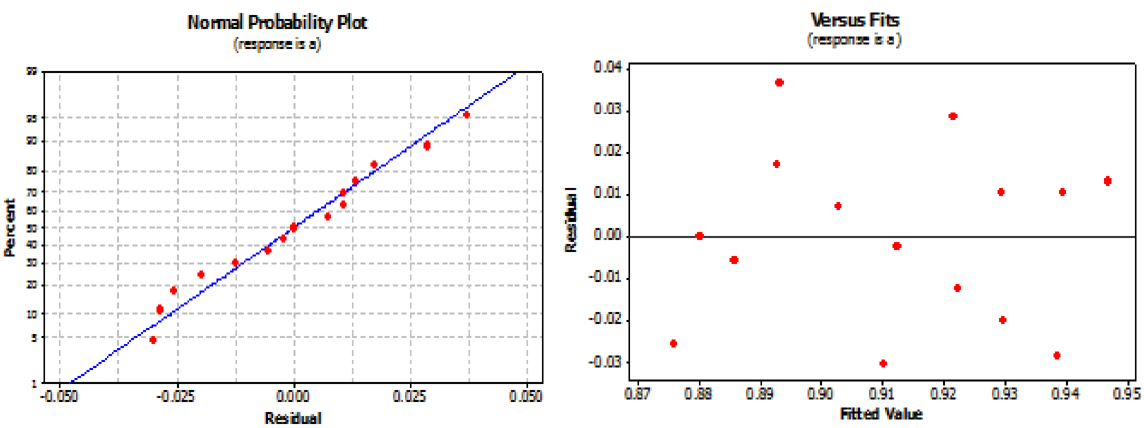

Figure A.23: Normal probability plot and versus fits for α for marl

Table A.24: General Linear Model for α versus Type of additives, Temperature and Deviator stress for Sabkha soil

Factor	Type		Levels	Values		
Type of additives	fixed		2	1, 2		
Temperature	fixed		2	1, 2		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for α, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of additives	1	0.09302	0.09302	0.09302	3.25	0.105
Temperature	1	0.01067	0.05070	0.05070	1.77	0.216
Deviator stress	4	0.14353	0.14353	0.03588	1.25	0.355
Error	9	0.25738	0.25738	0.02860		
Total	15	0.50460				
S = 0.169107 R-Sq = 48.99% R-Sq(adj) = 14.99%						

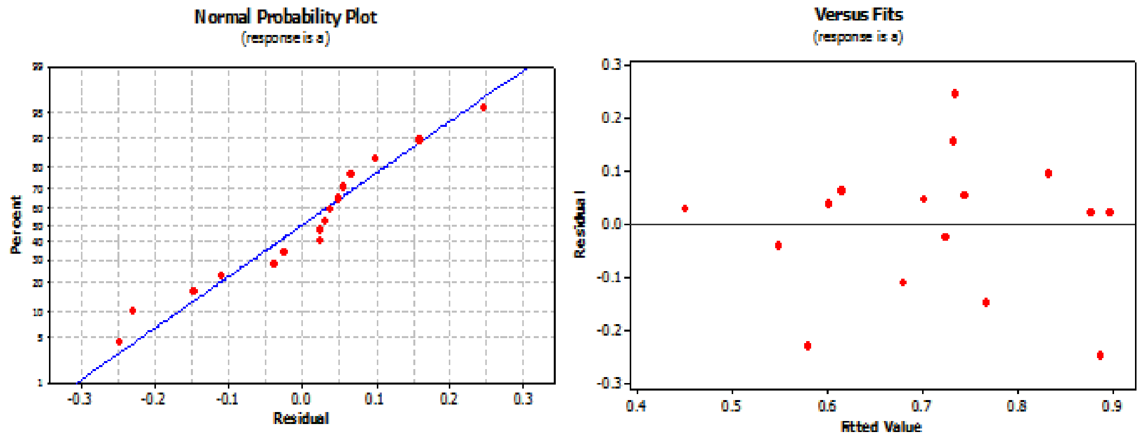

Figure A.24: Normal probability plot and versus fits for α for sabkha

Table A.25: General Linear Model for α versus Type of additives, Temperature and Deviator stress for Dune sand soil

Factor	Type		Levels	Values		
Type of additives	fixed		2	1, 2		
Temperature	fixed		2	1, 2		
Deviator stress	fixed		5	1, 2, 3, 4, 5		
Analysis of Variance for α, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of additives	1	0.20617	0.29726	0.29726	3.92	0.083
Temperature	1	0.19425	0.05741	0.05741	0.76	0.410
Deviator stress	4	0.24249	0.24249	0.06062	0.80	0.558
Error	8	0.60706	0.60706	0.07588		
Total	14	1.24997				
S = 0.275468 R-Sq = 51.43% R-Sq(adj) = 15.01%						

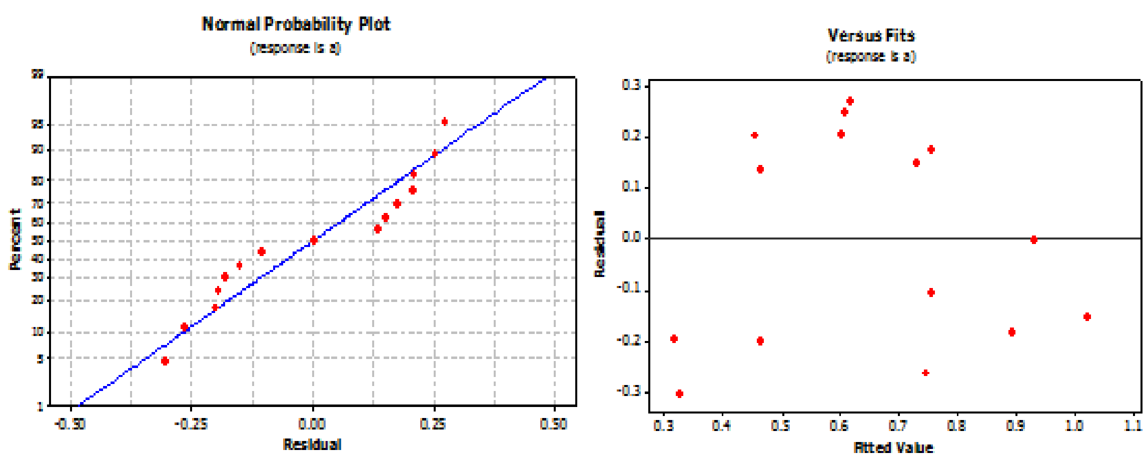

Figure A.25: Normal probability plot and versus fits for α for dune sand

Table A.26: Regression Analysis for a versus Additive, Deviator stress and Temperature for Marl

Regression Equation				
a = - 8156 + 6376 Additive + 1.77 Deviator stress, kPa + 82.3 Temperature				
Predictor	Coef	SE Coef	T	P
Constant	-8156	1549	-5.27	0.000
Type of additives	6376.5	631.7	10.09	0.000
Deviator stress	1.766	2.884	0.61	0.553
Temperature	82.29	37.66	2.18	0.051
Summary of Model				
S = 1203.02 R-Sq = 91.4% R-Sq(adj) = 89.0%				

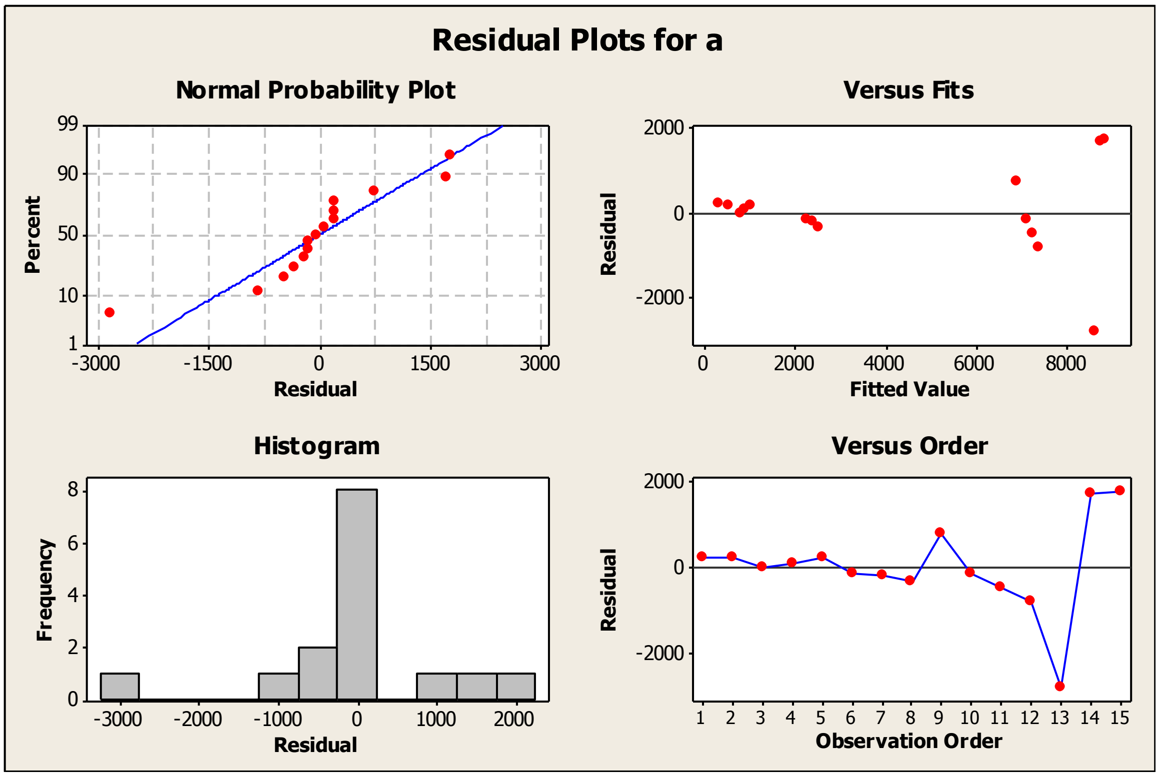

Figure A.26: Residual plot for rutting intercept (a) for marl versus Type of additives, Deviator stress, and Temperature

Table A.27: Regression Analysis for b versus Additive, Deviator stress and Temperature for Marl

Regression Equation				
b = 0.124 + 0.0033 Additive + 0.000055 Deviator stress - 0.00233 Temperature				
Predictor	Coef	SE Coef	T	P
Constant	0.12369	0.03632	3.41	0.006
Type of additives	0.00331	0.01481	0.22	0.827
Deviator stress	0.00005463	0.00006762	0.81	0.436
Temperature	-0.0023339	0.0008830	-2.64	0.023
Summary of Model				
S = 0.0282060 R-Sq = 39.1% R-Sq(adj) = 22.4%				

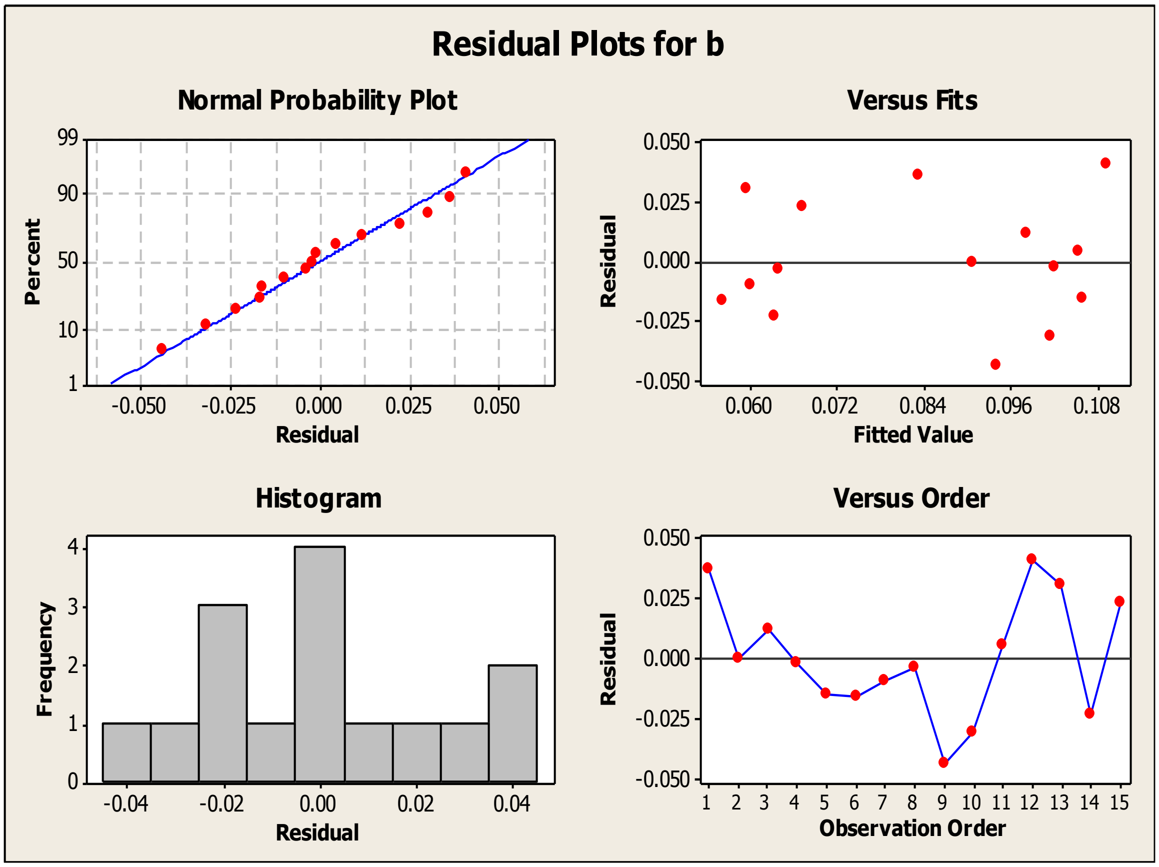

Figure A.27: Residual plot for rutting slop (b) for marl versus Type of additives, Deviator stress, and Temperature

Table A.28: Regression Analysis for a versus Additive, Deviator stress and Temperature for Sabkha

Regression Equation				
a = - 5170 + 2605 Additive - 6.64 Deviator stress, kPa + 319 Temperature				
Predictor	Coef	SE Coef	T	P
Constant	-5170	5000	-1.03	0.322
Type of additives	2605	2014	1.29	0.220
Deviator stress	-6.645	8.229	0.81	0.435
Temperature	319.1	126.1	2.53	0.026
Summary of Model				
S = 4028.59 R-Sq = 40.4% R-Sq(adj) = 25.5%				

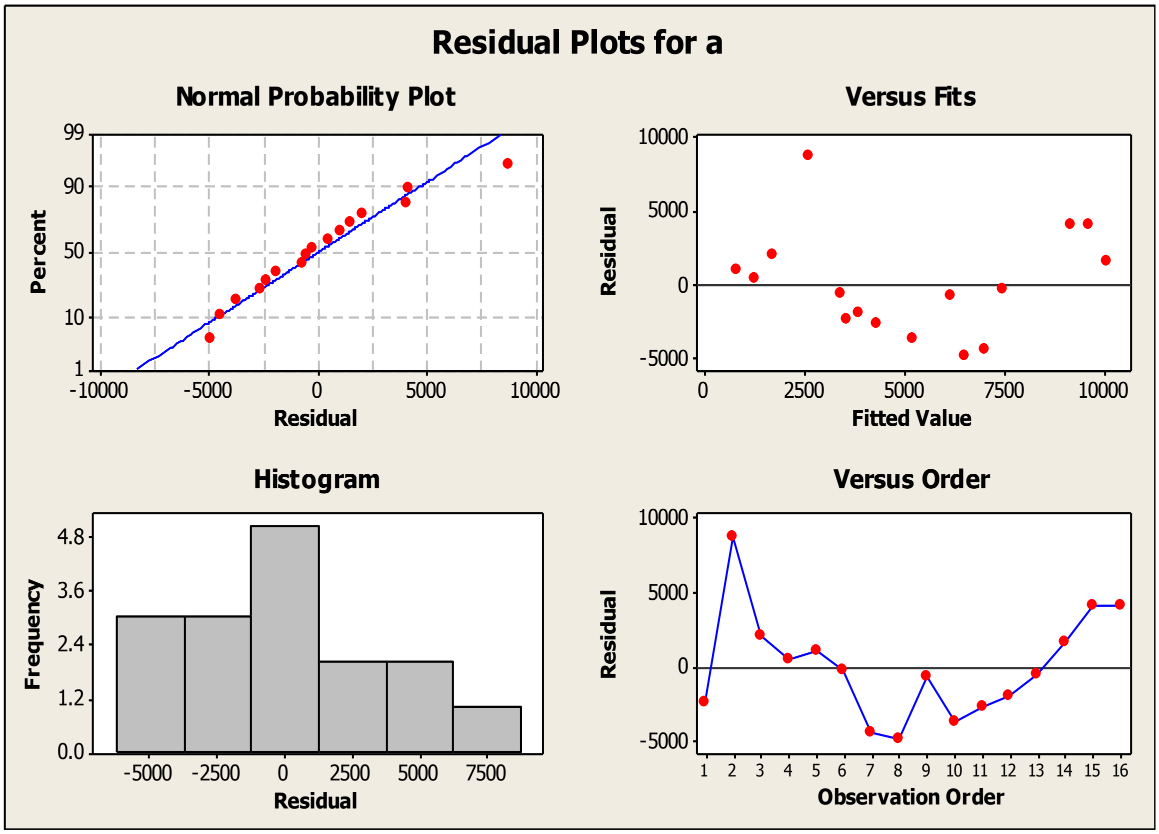

Figure A.28: Residual plot for rutting intercept (a) for sabkha versus Type of additives, Deviator stress, and Temperature

Table A.29: Regression Analysis for b versus Additive, Deviator stress and Temperature for sabkha

Regression Equation				
b = 0.433 - 0.154 Additive + 0.000718 Deviator stress, kPa - 0.00731 Temperature				
Predictor	Coef	SE Coef	T	P
Constant	0.4332	0.1879	2.31	0.040
Type of additives	-0.15375	0.07570	-2.03	0.065
Deviator stress	0.0007175	0.0003093	2.32	0.039
Temperature	-0.007306	0.004739	-1.54	0.149
Summary of Model				
S = 0.151402 R-Sq = 45.3% R-Sq(adj) = 31.7%				

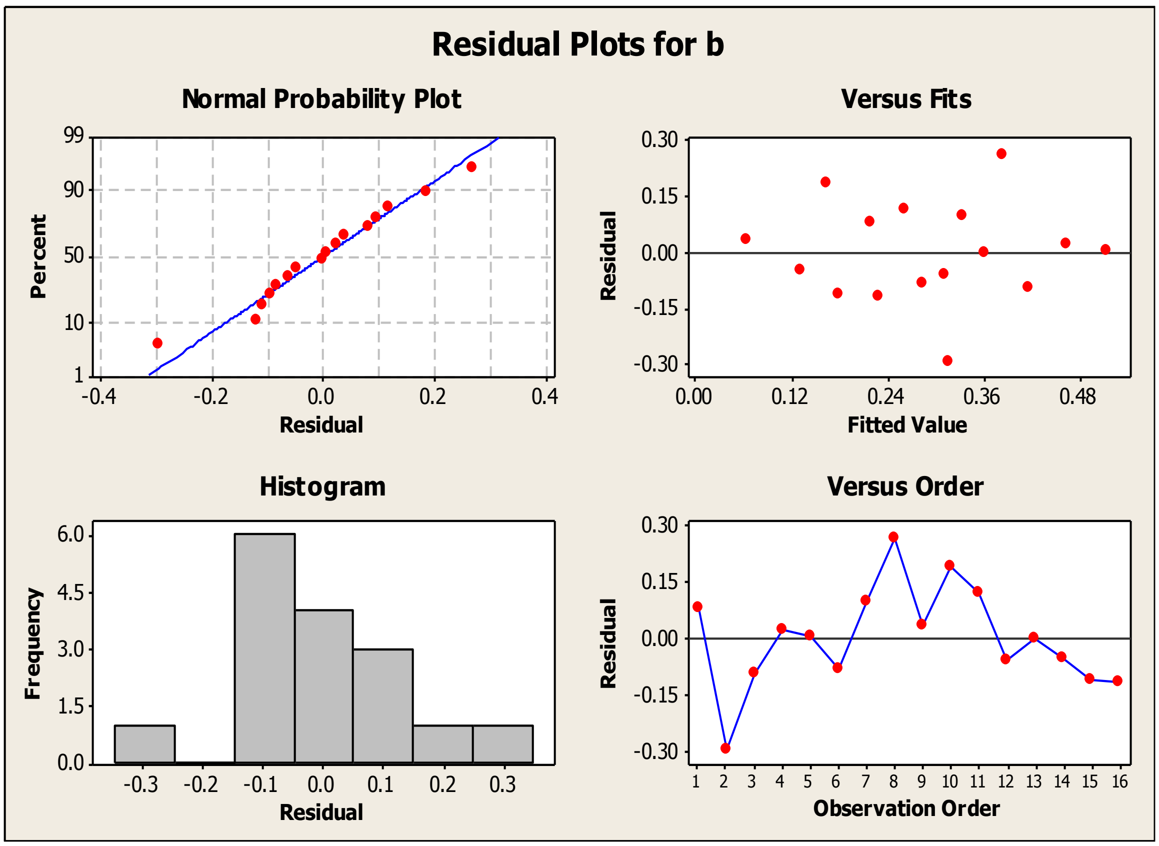

Figure A.28: Residual plot for rutting slop (b) for sabkha versus Type of additives, Deviator stress, and Temperature

Table A.30: Regression Analysis for a versus Additive, Deviator stress and Temperature for Dune Sand

Regression Equation				
a = - 838 + 1847 Additive - 2.33 Deviator stress, kPa + 32.0 Temperature				
Predictor	Coef	SE Coef	T	P
Constant	-837.5	874.3	-0.96	0.359
Type of additives	1846.8	356.5	5.18	0.000
Deviator stress	-2.326	1.628	-1.43	0.181
Temperature	32.04	21.26	1.51	0.160
Summary of Model				
S = 679.019 R-Sq = 72.5% R-Sq(adj) = 65.0%				

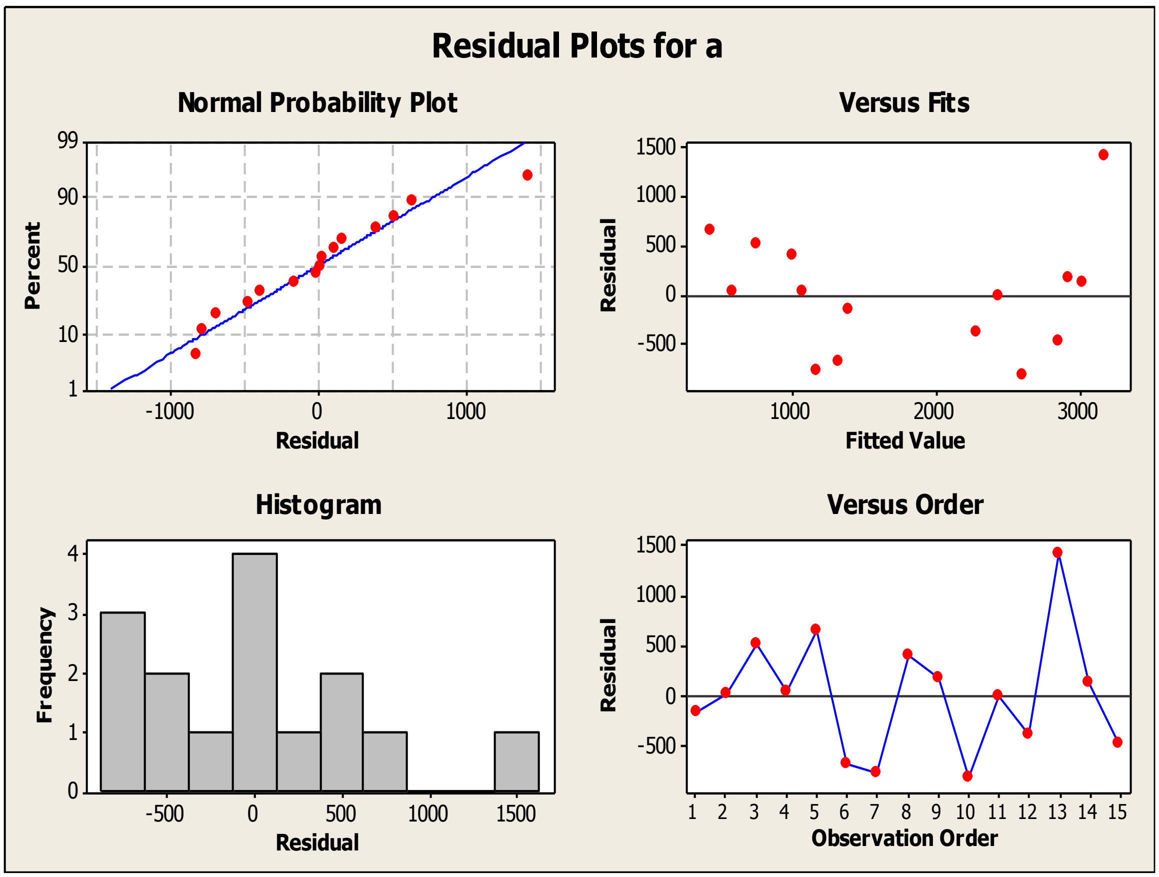

Figure A.30: Residual plot for rutting intercept (a) for sand versus Type of additives, Deviator stress, and Temperature

Table A.31: Regression Analysis: b versus Additive, Deviator stress and Temperature for dune sand

Regression Equation				
b = 0.051 - 0.288 Additive + 0.00115 Deviator stress, kPa + 0.00780 Temperature				
Predictor	Coef	SE Coef	T	P
Constant	0.0515	0.3071	0.17	0.870
Type of additives	-0.2880	0.1252	-2.30	0.042
Deviator stress	0.0011536	0.0005718	2.02	0.069
Temperature	0.007803	0.007468	1.04	0.319
Summary of Model				
S = 0.238539 R-Sq = 50.4% R-Sq(adj) = 36.9%				

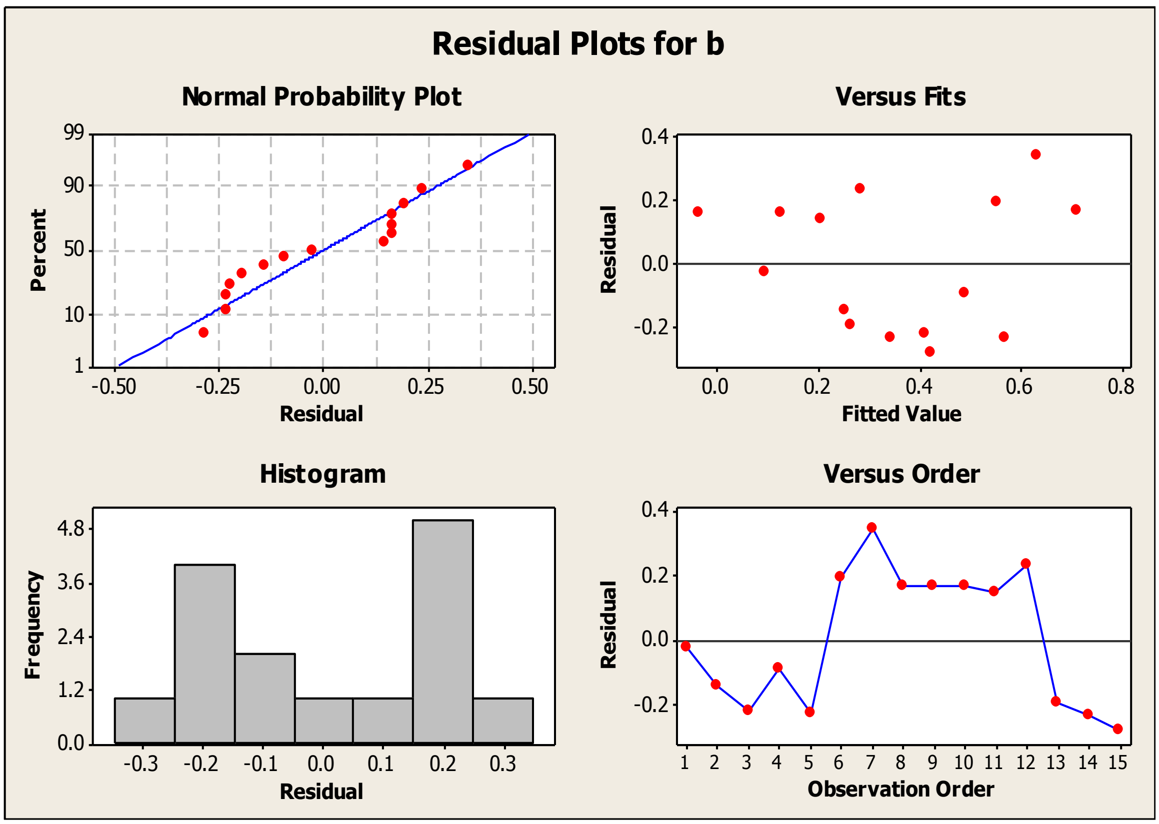

Figure A.31: Residual plot for rutting slop (b) for sand versus Type of additives, Deviator stress, and Temperature

Table A.32: General Regression Analysis for μ versus Type of additives, Temperature and Deviator stress for Marl soil

Regression Equation				
μ = -1.0149 + 1.01948 Type of additives - 0.00768187 Temperature + 0.000948879 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	-1.01490	0.349156	-2.90673	0.014
Type of additives	1.01948	0.142386	7.15997	0.000
Temperature	-0.00768	0.008490	-0.90485	0.385
Deviator stress	0.00095	0.000650	1.45966	0.172
Summary of Model				
S = 0.271175 R-Sq = 84.11% R-Sq(adj) = 79.78% PRESS = 1.60317 R-Sq(pred) = 68.51%				

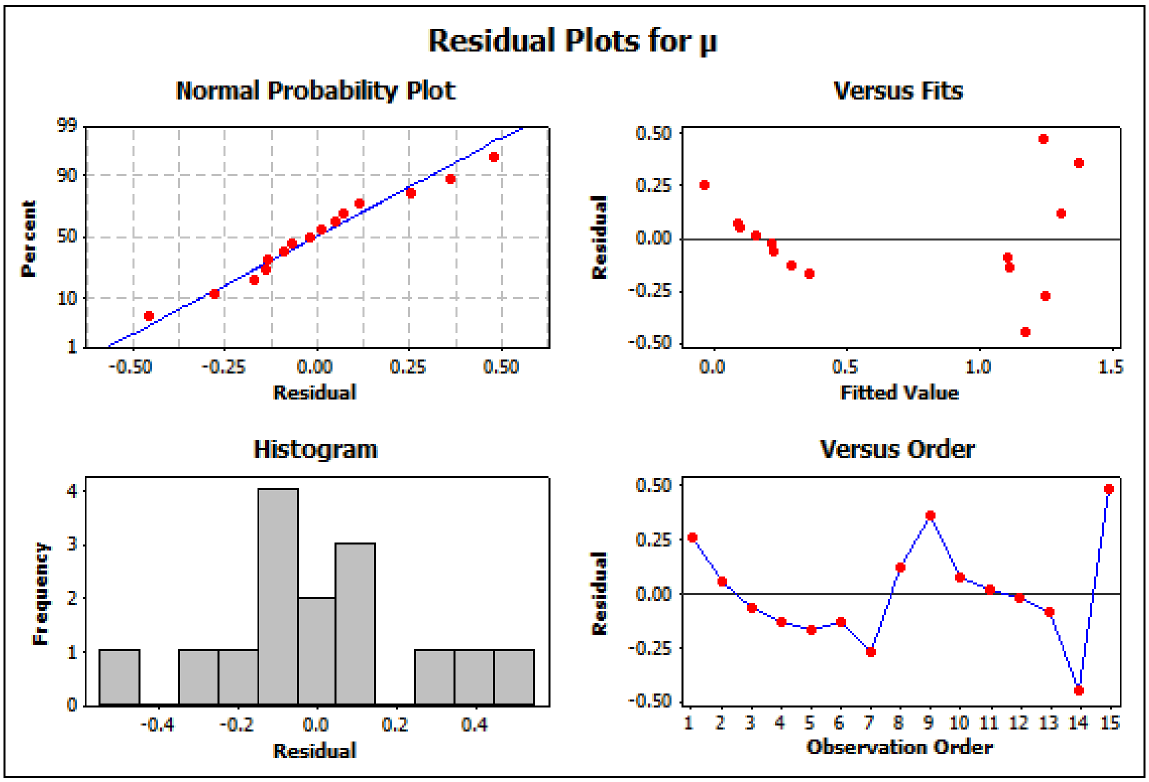

Figure A.32: Residual plot for μ for marl versus Type of additives, Deviator stress, and Temperature

Table A.33: General Regression Analysis for μ versus Type of additives, Temperature and Deviator stress for Sabkha soil

Regression Equation				
μ = 0.692193 - 0.26625 Type of additives + 0.0507021 Temperature - 0.000177987 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	0.692193	0.754198	0.91779	0.377
Type of additives	-0.266250	0.303822	-0.87634	0.398
Temperature	0.050702	0.019020	2.66567	0.021
Deviator stress	-0.000178	0.001241	-0.14340	0.888
Summary of Model				
S = 0.607643 R-Sq = 42.55% R-Sq(adj) = 28.19% PRESS = 1.60317 R-Sq(pred) = 68.51%				

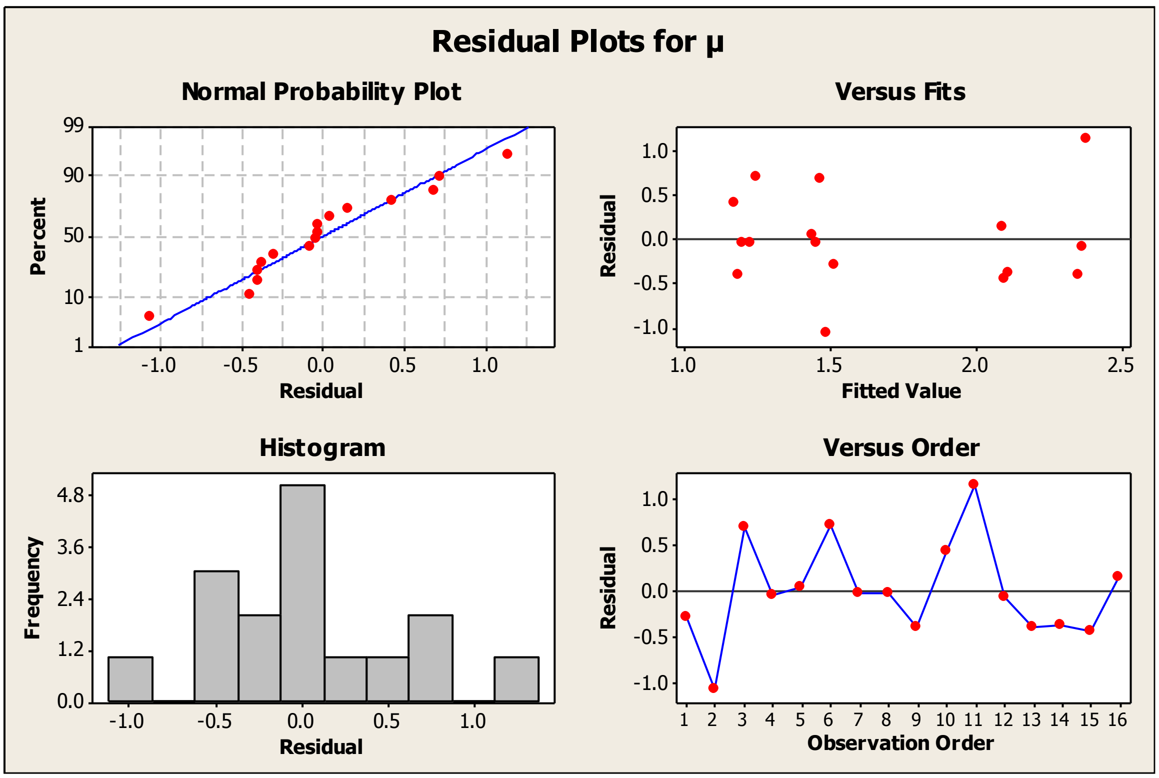

Figure A.33: Residual plot for μ for sabkha versus Type of additives, Deviator stress, and Temperature

Table A.34: General Regression Analysis for μ versus Type of additives, Temperature and Deviator stress for Dune sand soil

Regression Equation				
μ = 0.0327032 + 0.420171 Type of additives - 0.0206515 Temperature + 0.00139809 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	0.032703	0.331372	0.09869	0.923
Type of additives	0.420171	0.135133	3.10931	0.010
Temperature	-0.020651	0.008057	-2.56308	0.026
Deviator stress	0.001398	0.000617	2.26610	0.045
Summary of Model				
S = 0.257363 R-Sq = 64.96% R-Sq(adj) = 55.40% PRESS = 1.37218 R-Sq(pred) = 34.00%				

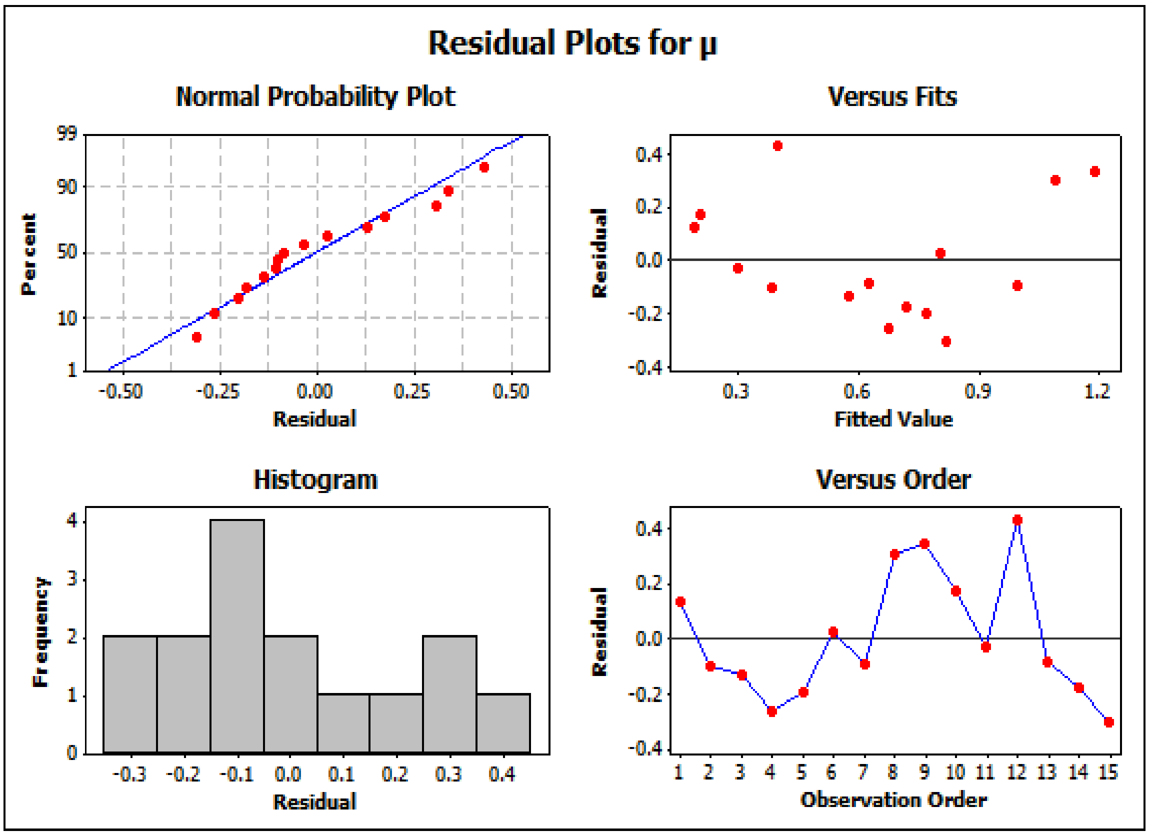

Figure A.34: Residual plot for μ for sand versus Type of additives, Deviator stress, and Temperature

Table A.35: General Regression Analysis for μ versus Type of additives, Type of Soil, Temperature and Deviator stress

Regression Equation				
μ = -0.0443548 + 0.40813 Type of additives - 0.008 Type of Soil + 0.00751633 Temperature + 0.000589949 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	-0.044355	0.612473	-0.07242	0.943
Type of additives	0.408130	0.222293	1.83600	0.074
Type of Soil	-0.008000	0.136786	-0.05849	0.954
Temperature	0.007516	0.013541	0.55508	0.582
Deviator stress	0.000590	0.000971	0.60774	0.547
Summary of Model				
S = 0.749206 R-Sq = 62% R-Sq(adj) = 1.78% PRESS = 28.3082 R-Sq(pred) = -65%				

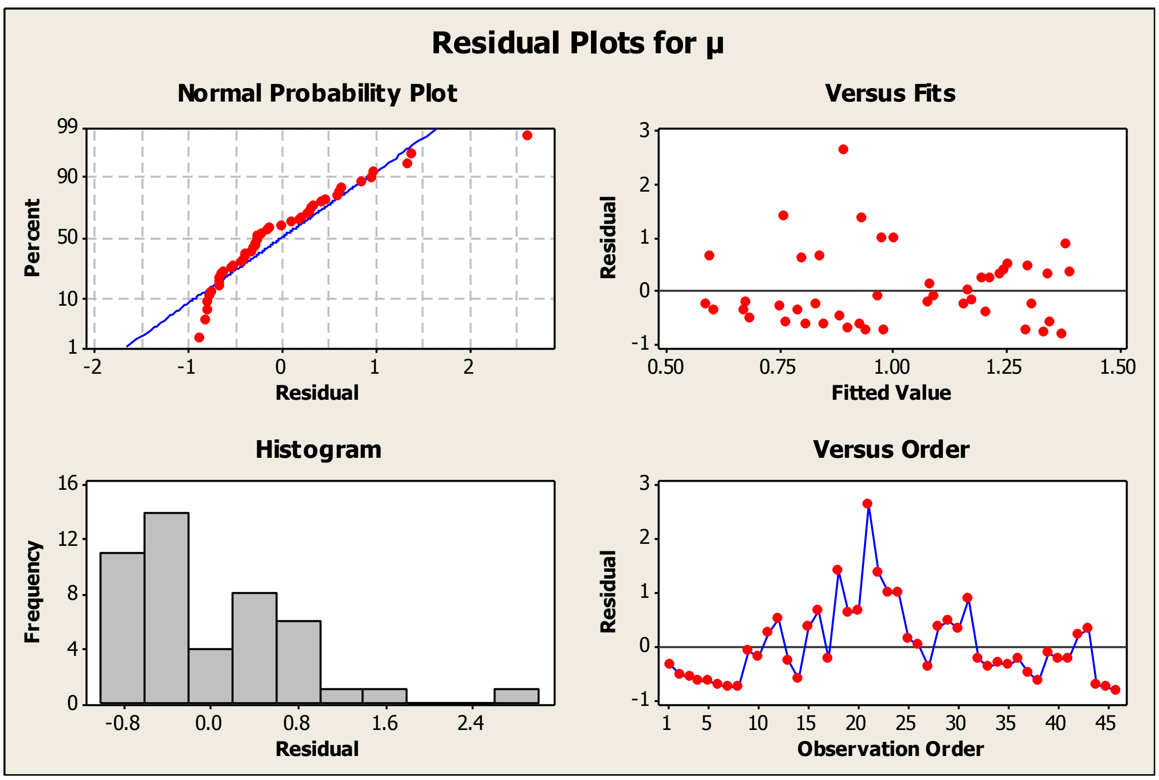

Figure A.35: Residual plot for μ versus Type of additives, Deviator stress, Type of Soil and Temperature

Table A.36: General Regression Analysis for α versus Type of additives, Temperature and Deviator stress for Marl soil

Regression Equation				
μ = 0.894025 - 0.0117052 Type of additives + 0.00193391 Temperature - 0.00005 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	0.894025	0.0366331	24.4048	0.000
Type of additives	-0.011705	0.0149390	-0.7835	0.450
Temperature	0.001934	0.0008907	2.1711	0.053
Deviator stress	-0.000049	0.0000682	-0.7237	0.484
Summary of Model				
S = 0.0284515 R-Sq = 32.75% R-Sq(adj) = 14.40% PRESS = 0.0199409 R-Sq(pred) = -50.61%				

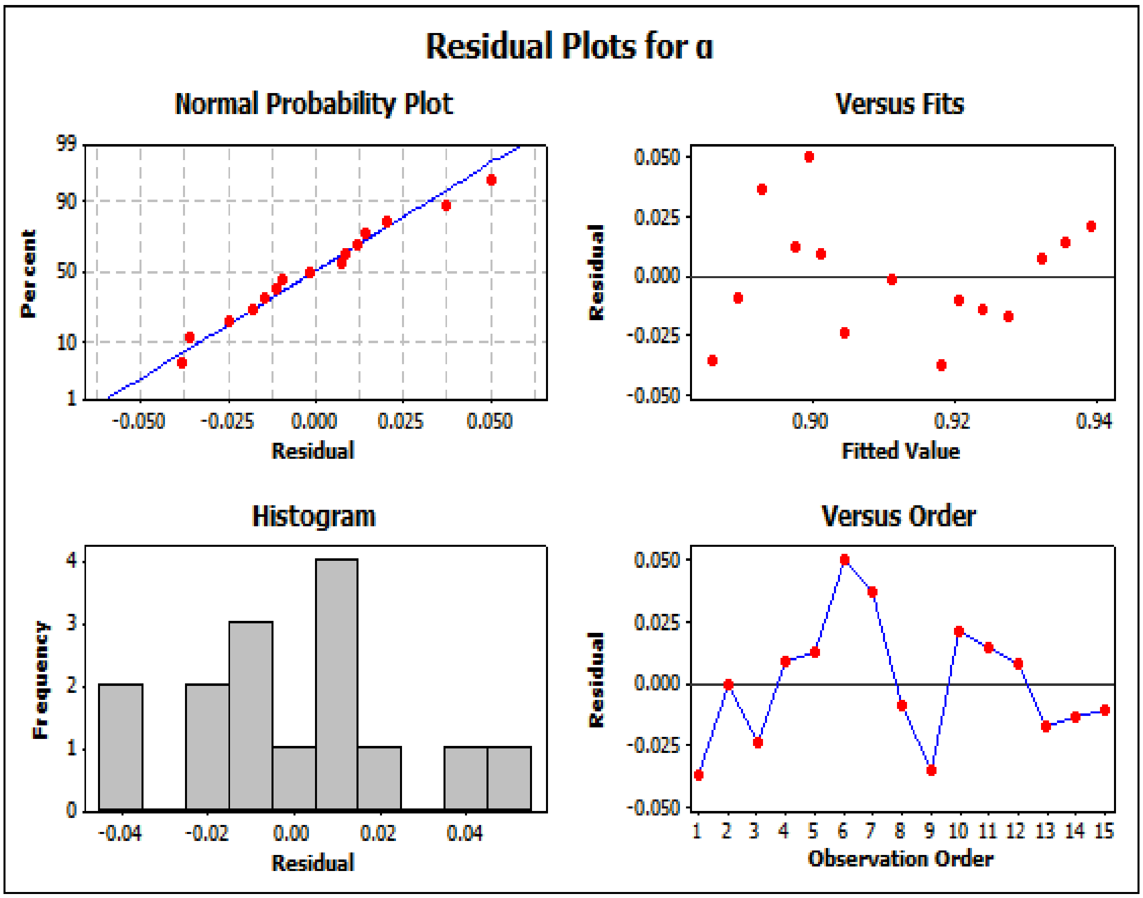

Figure A.36: Residual plot for α for marl versus Type of additives, Deviator stress, and Temperature

Table A.37: General Regression Analysis for α versus Type of additives, Temperature and Deviator stress for Sabkha soil

Regression Equation				
α = 0.565485 + 0.1525 Type of additives + 0.00733647 Temperature - 0.000713503 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	0.565485	0.189220	2.98851	0.011
Type of additives	0.152500	0.076225	2.00065	0.069
Temperature	0.007336	0.004772	1.53740	0.150
Deviator stress	-0.000714	0.000311	-2.29127	0.041
Summary of Model				
S = 0.152451 R-Sq = 44.73% R-Sq(adj) = 30.91% PRESS = 0.465692 R-Sq(pred) = 7.71%				

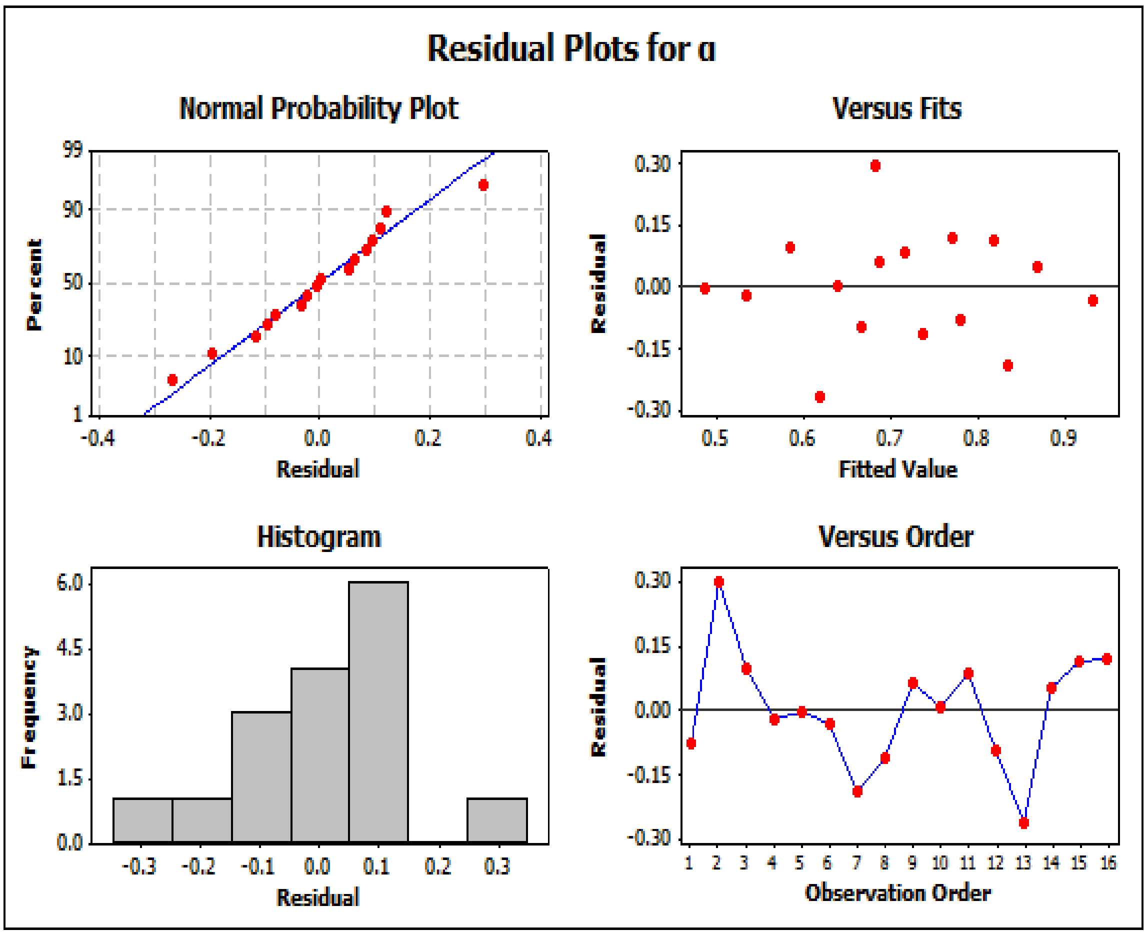

Figure A.37: Residual plot for α for sabkha versus Type of additives, Deviator stress, and Temperature

Table A.38: General Regression Analysis for α versus Type of additives, Temperature and Deviator stress for Dune sand soil

Regression Equation				
α = 0.943446 + 0.287725 Type of additives - 0.00766241 Temperature - 0.00115036 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	0.943446	0.305501	3.08819	0.010
Type of additives	0.287725	0.124583	2.30951	0.041
Temperature	-0.007662	0.007428	-1.03153	0.324
Deviator stress	-0.001150	0.000569	-2.02247	0.068
Summary of Model				
S = 0.237270 R-Sq = 50.46% R-Sq(adj) = 36.95% PRESS = 1.11632 R-Sq(pred) = 10.69%				

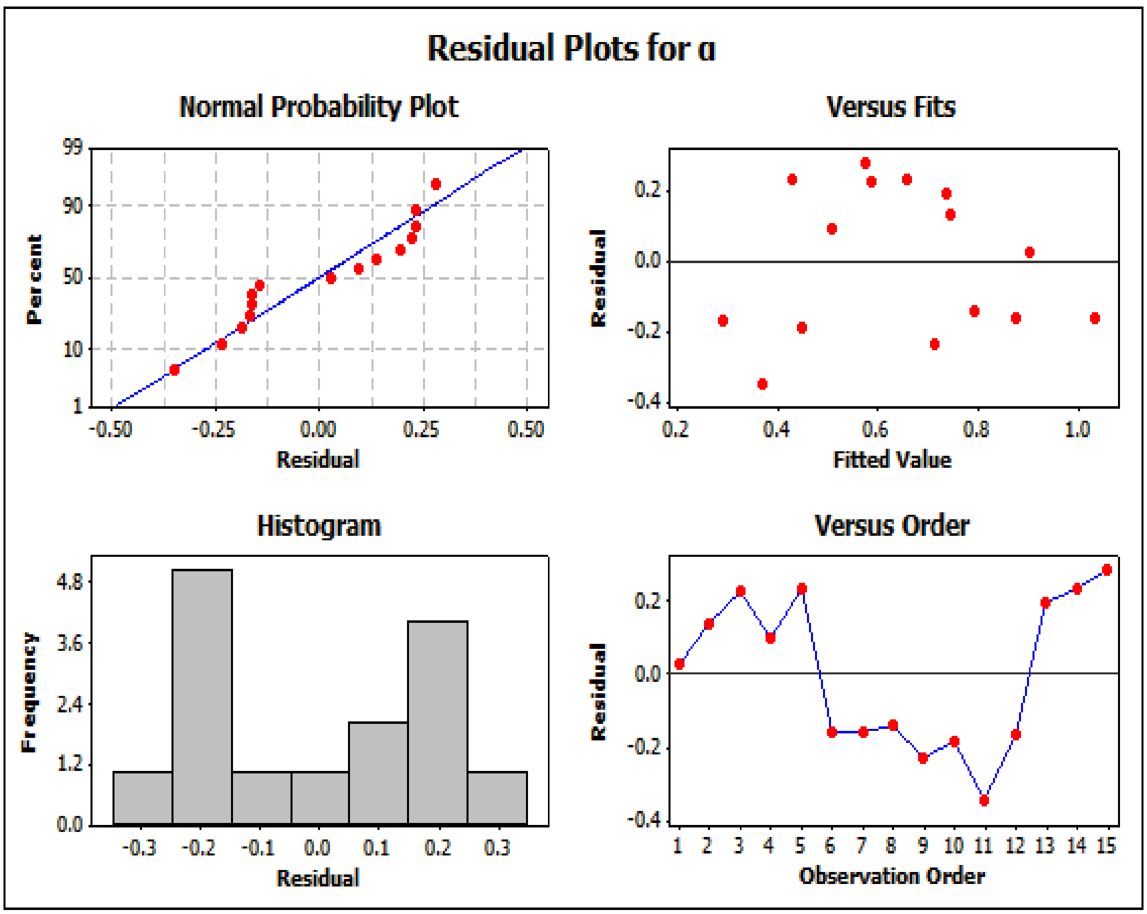

Figure A.38: Residual plot for α for sand versus Type of additives, Deviator stress, and Temperature

Table A.39: General Regression Analysis for α versus Type of additives, Temperature, Type of Soil and Deviator stress

Regression Equation				
α = 1.05904 + 0.138496 Type of additives - 0.133667 Type of SOIL + 0.000520636 Temperature - 0.000603743 Deviator stress				
Predictor	Coef	SE Coef	T	P
Constant	1.05904	0.151064	7.01052	0.000
Type of additives	0.13850	0.054828	2.52603	0.015
Type of Soil	-0.13367	0.033738	-3.96194	0.000
Temperature	0.00052	0.003340	0.15589	0.877
Deviator stress	-0.00060	0.000239	-2.52163	0.016
Summary of Model				
S = 0.184789 R-Sq = 40.49% R-Sq(adj) = 34.68% PRESS = 1.77328 R-Sq(pred) = 24.62%				

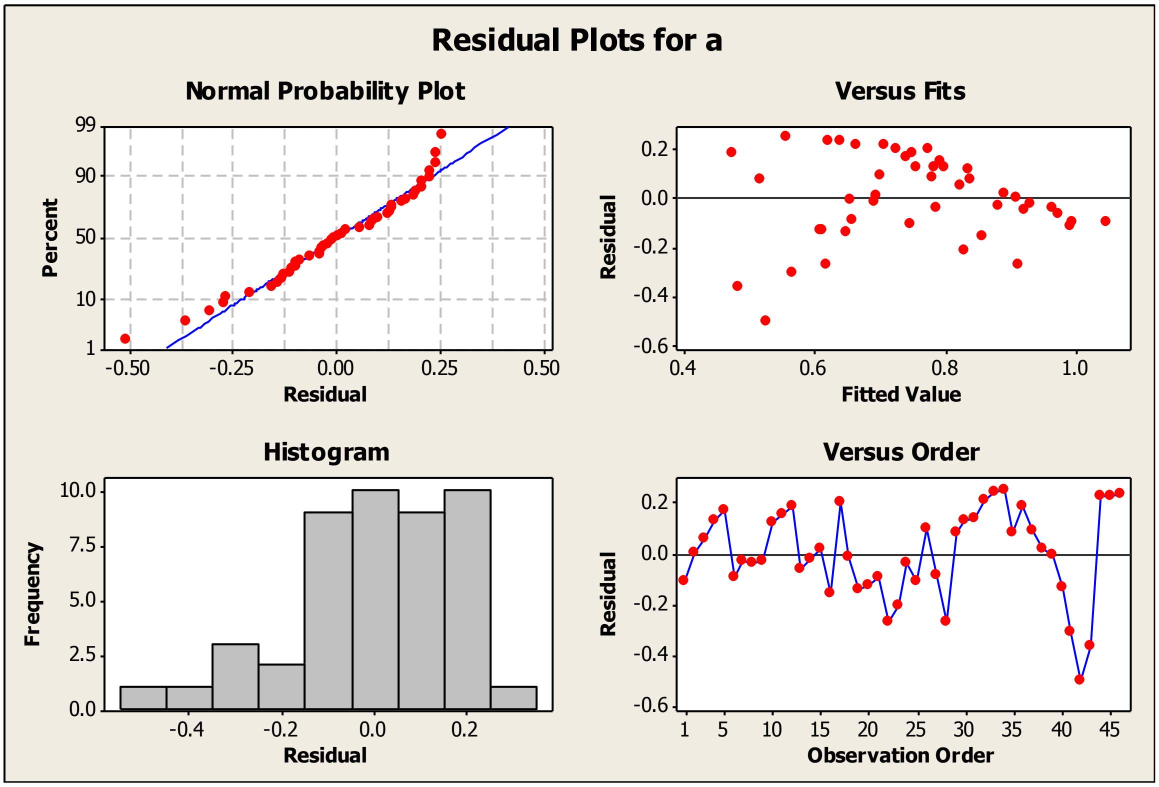

Figure A.39: Residual plot for α versus Type of additives, Deviator stress, Type of Soil and Temperature

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Table A.40: Regression Analysis for τ versus Type of soils, Type of additives, and normal stress

Regression Equation				
$\tau = 306 - 89.5$ soil type - 41.1 type of additive + 0.624 σ				
Predictor	Coef	SE Coef	T	P
Constant	305.97	73.20	4.18	0.001
Soil type	-89.48	15.35	-5.83	0.000
Type of additives	-41.15	24.34	-1.69	0.113
Deviator stress	0.62375	0.08886	7.02	0.000
Summary of Model				
S = 50.7075 R-Sq = 90.1% R-Sq(adj) = 88.0%				

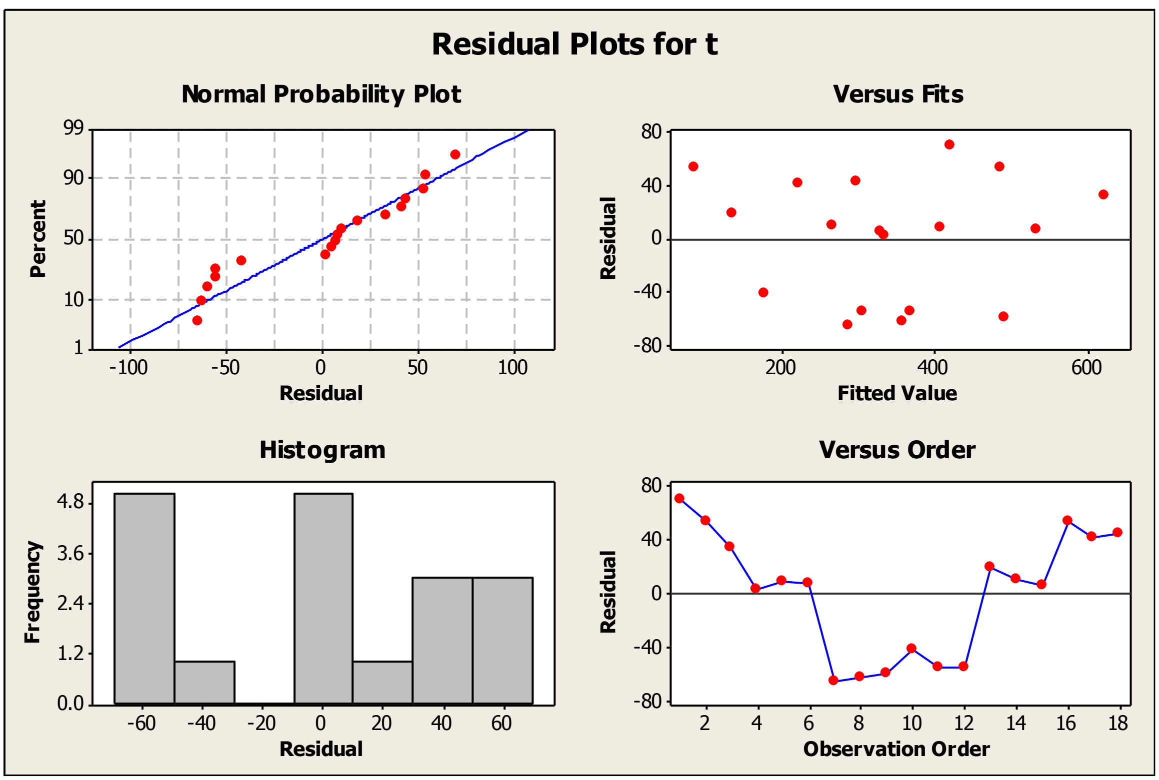

Figure A.40: Residual plot for shear stress versus Type of soils, Type of additives, and normal stress

APPENDIX B

Modeling production and results

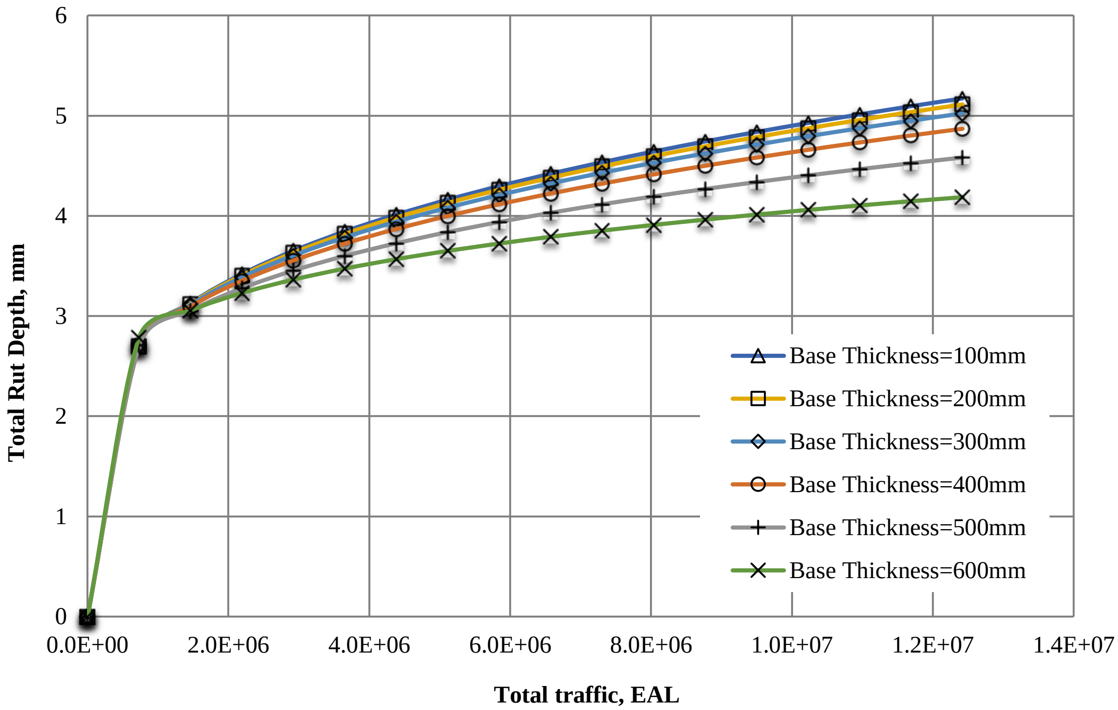

Figure B.1: Relationship between rut depth, total traffic and base thickness (case 1).

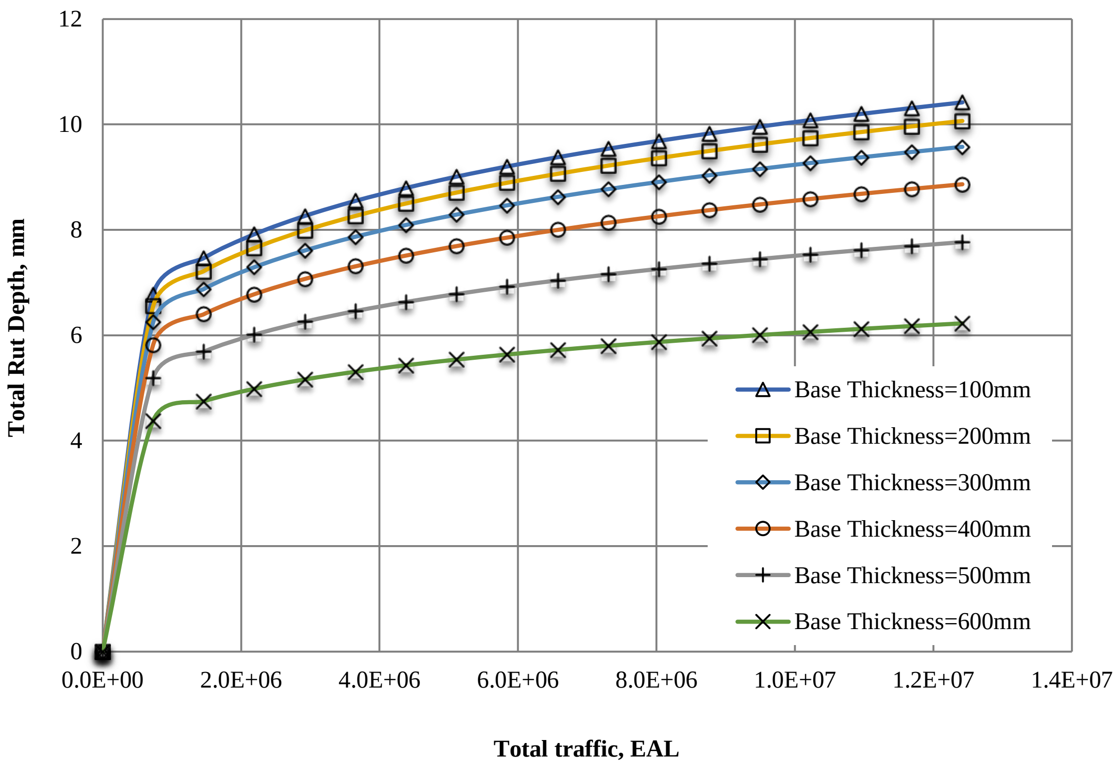

Figure B.2: Relationship between rut depth, total traffic and base thickness (case 2).

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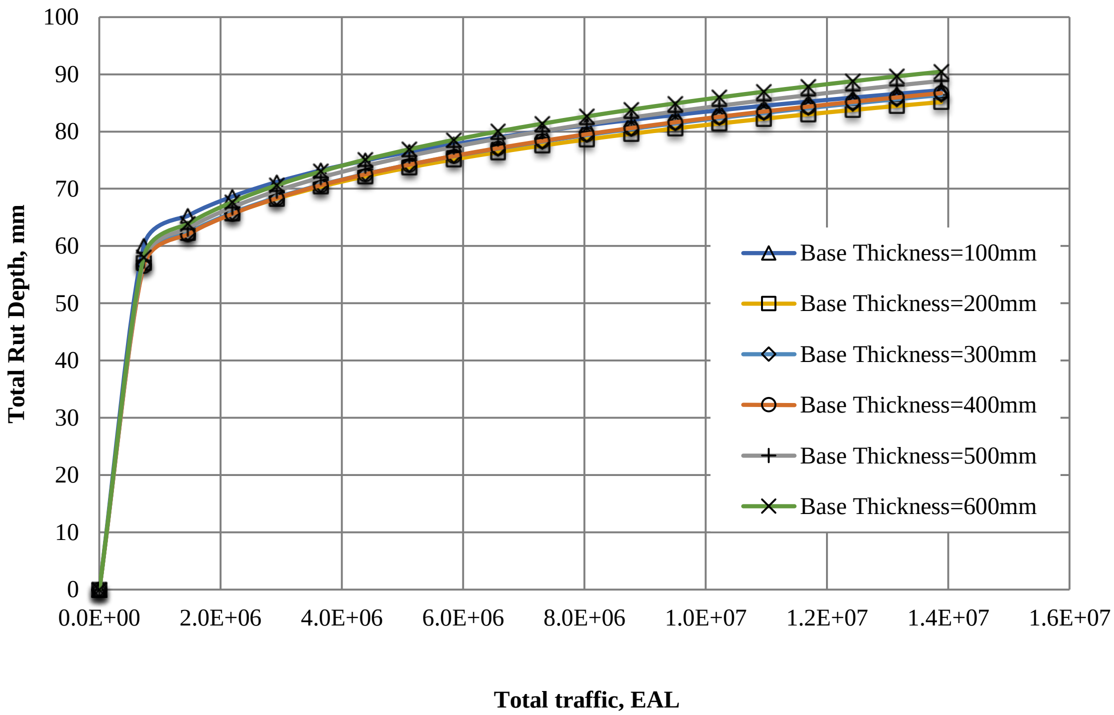

Figure B.3 Relationship between rut depth, total traffic and base thickness (case 3).

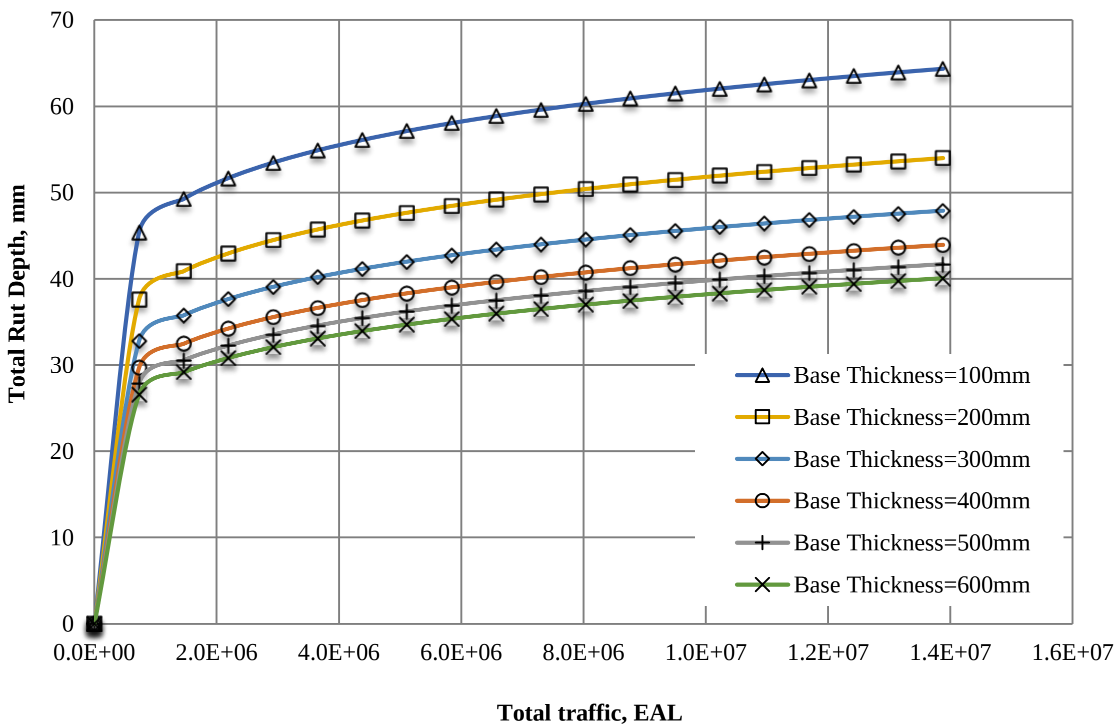

Figure B.4: Relationship between rut depth, total traffic and base thickness (case 4).

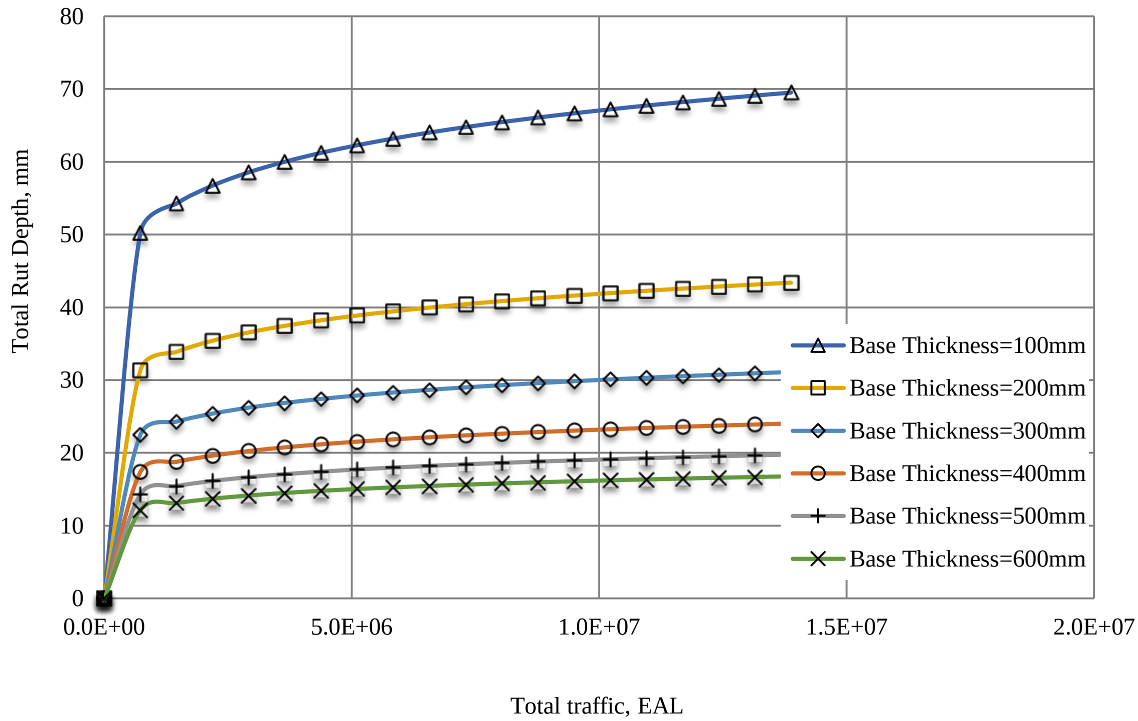

Figure B.5: Relationship between rut depth, total traffic and base thickness (case 5).

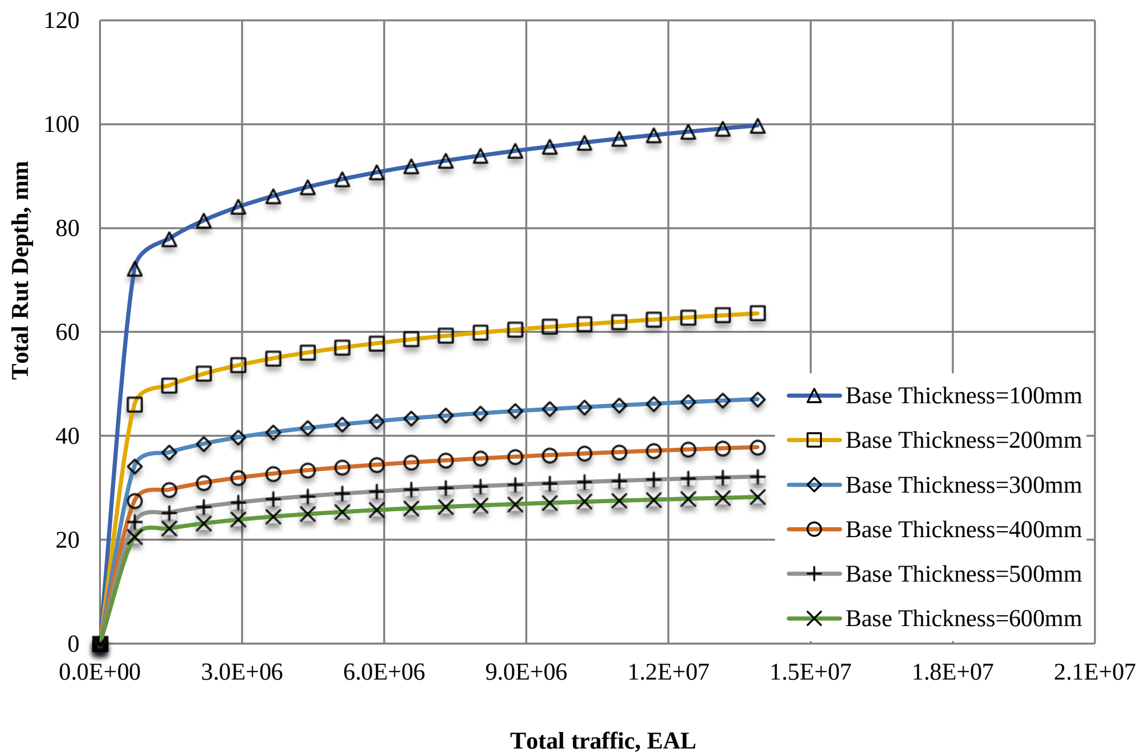

Figure B.6: Relationship between rut depth, total traffic and base thickness (case 6).

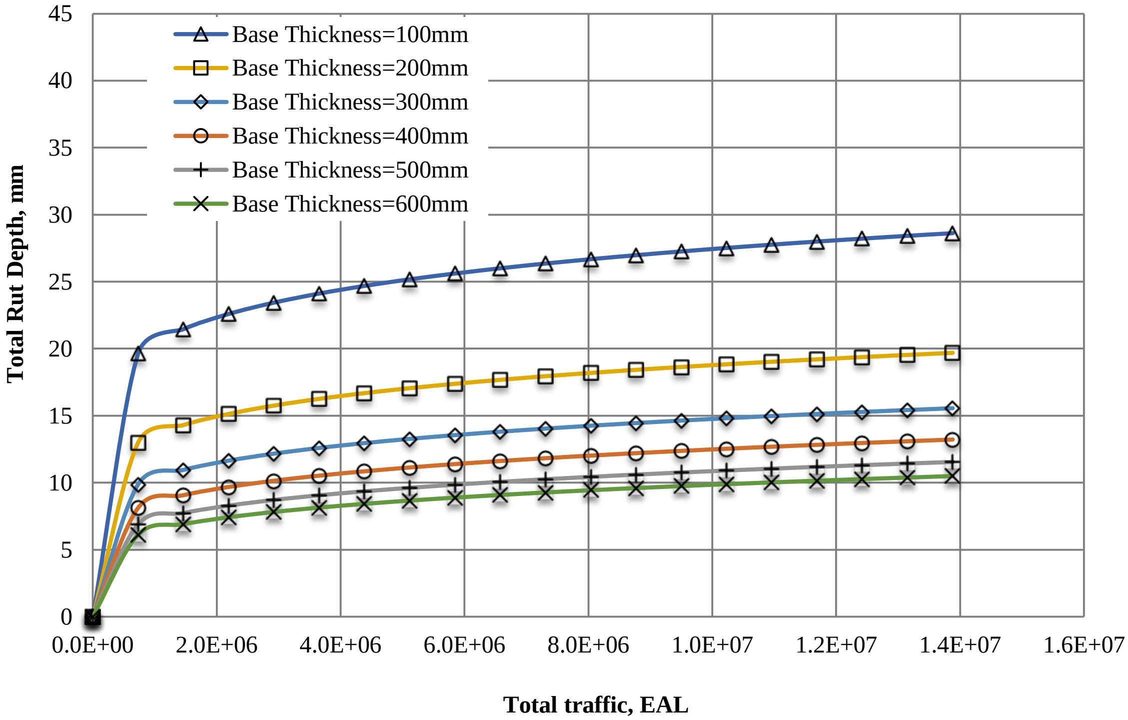

Figure B.7: Relationship between rut depth, total traffic and base thickness (case 7).

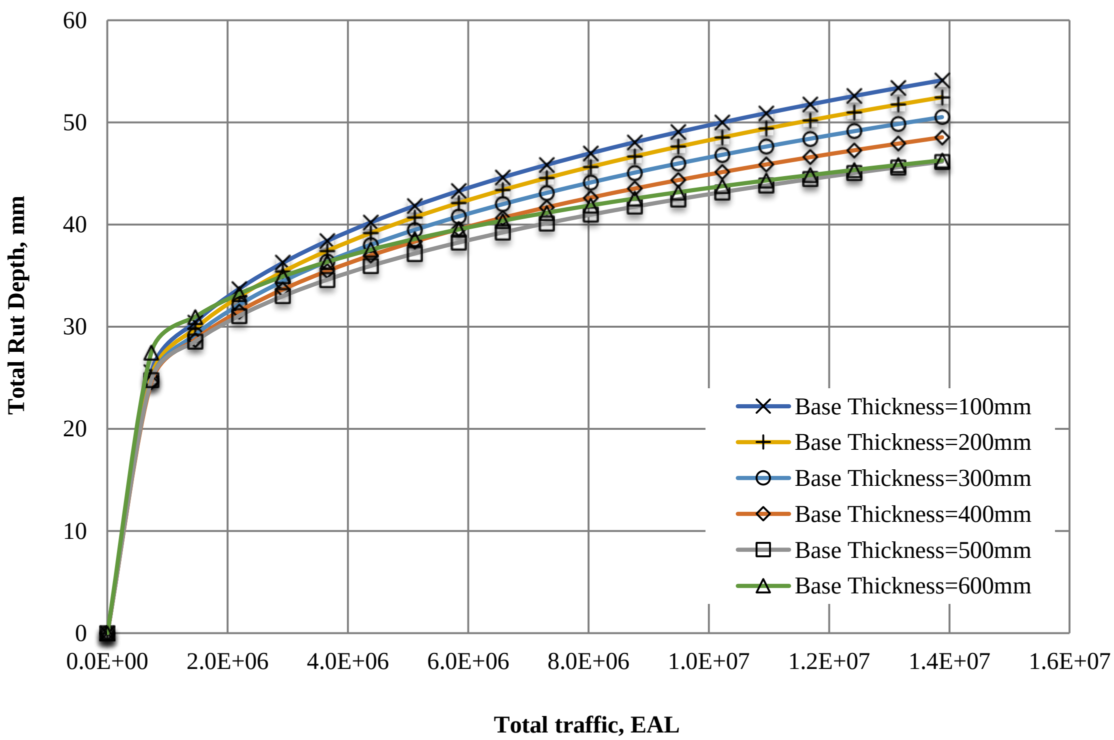

Figure B.8: Relationship between rut depth, total traffic and base thickness (case 8).

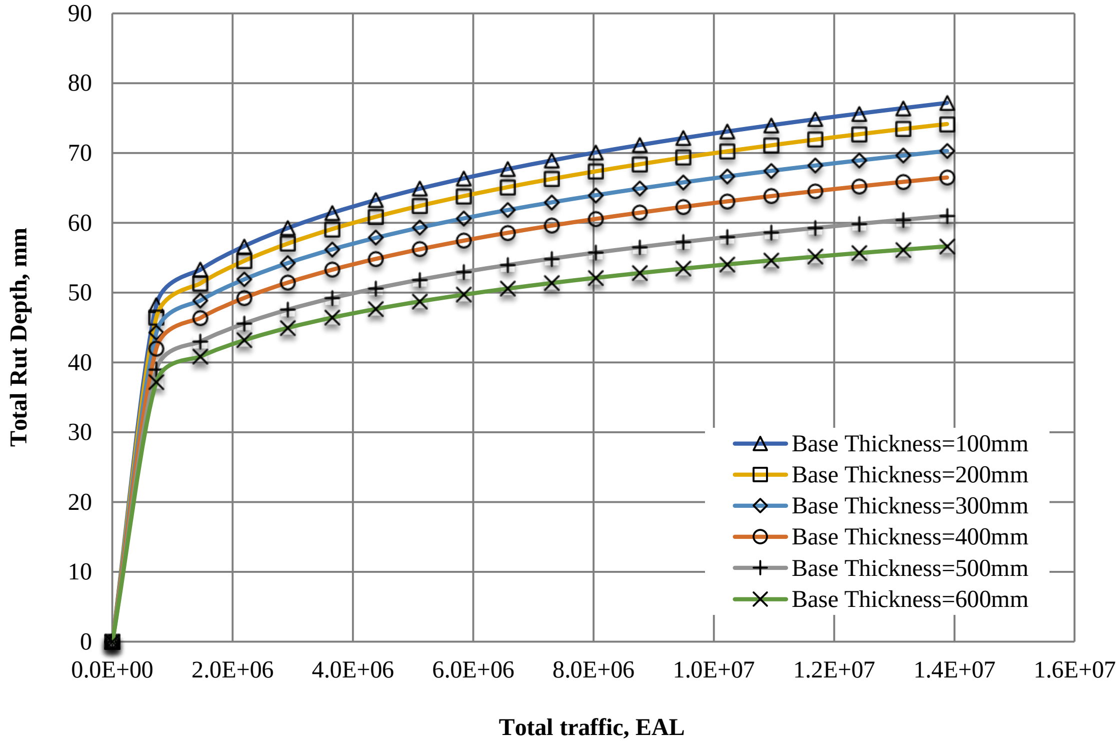

Figure B.9: Relationship between rut depth, total traffic and base thickness (case 9).

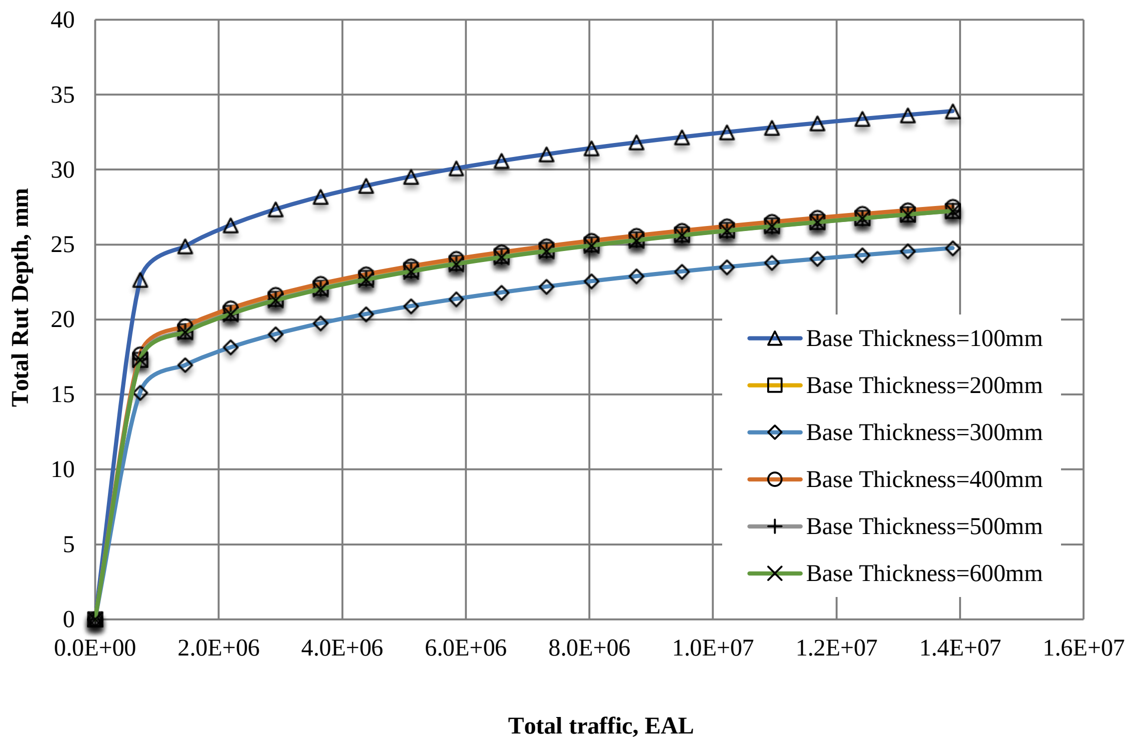

Figure B.10: Relationship between rut depth, total traffic and base thickness (case 10).

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